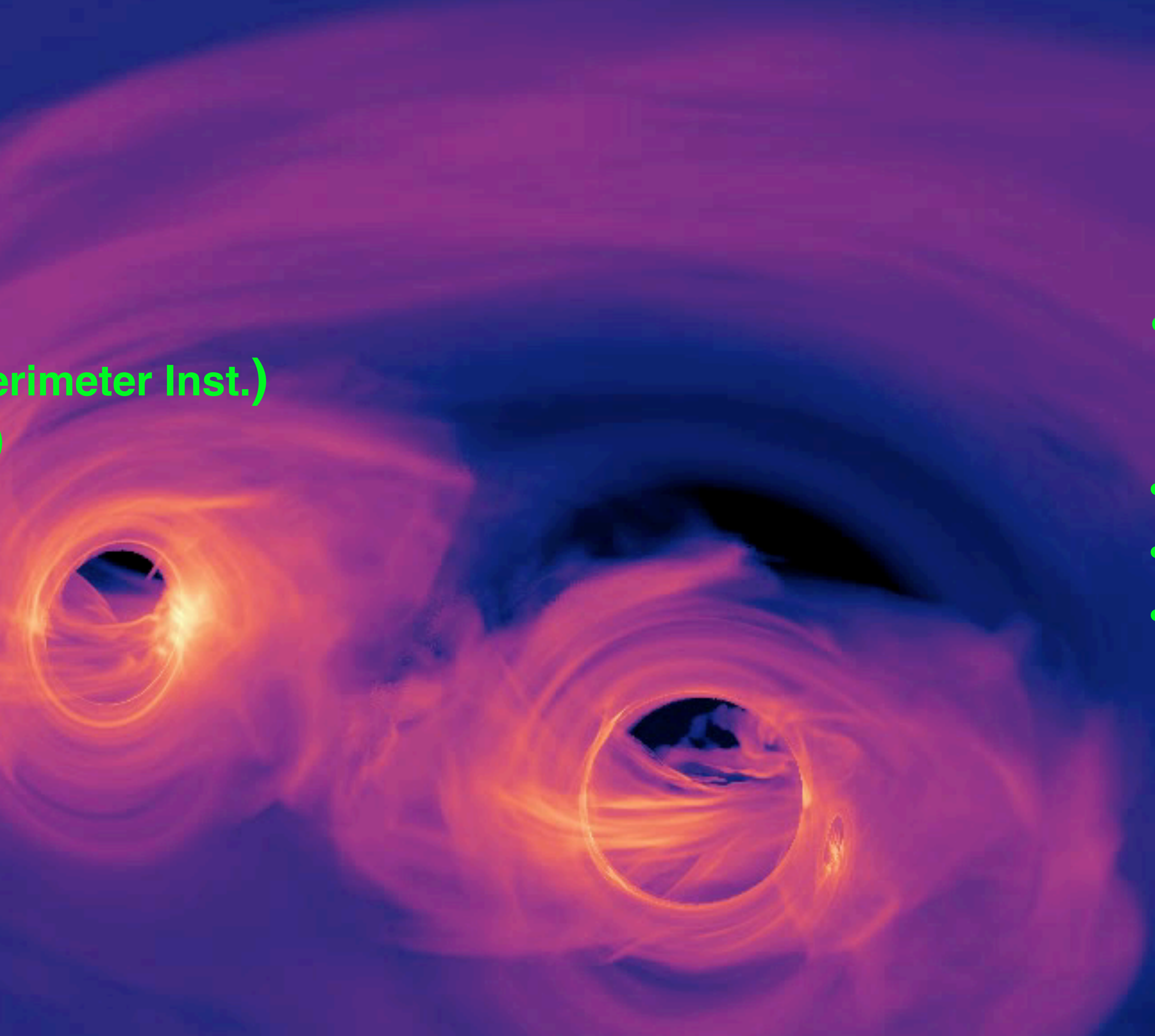
Time and Wavelength Domain Predictions for Accreting Binary Black Holes



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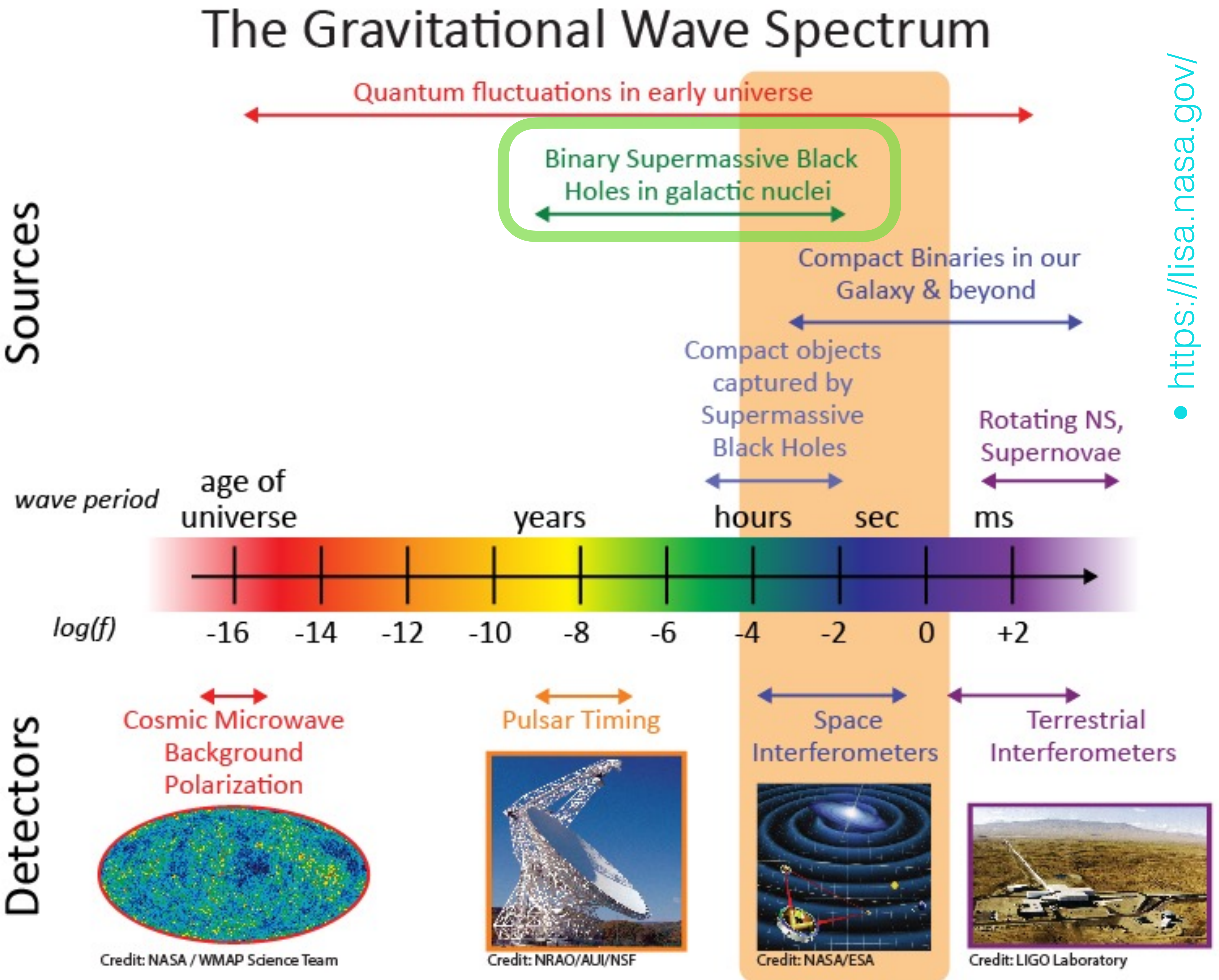
Massive Binary Black Holes

- Binary AGN are a primary multi-messenger source for LISA (inspirals, mergers, ringdowns) and PTA (inspirals).
- With joint GW+EM measurements:
  - Best candidate for exploring plasma physics in the strongest and most dynamical regime of gravity, allowing us to measure radiative efficiencies and feeding rate.
  - Allow us to look at entire life cycle of MBBHs, from kpc scales (EM) to merger/post-merger (GW+EM);
  - Improve the M in M-sigma;
  - Perform precision cosmology by measure redshifts and distances with same systems;
  - Affect GW analysis, e.g., gravitational torque from gas can affect SNR of EMRI LISA sources: Derdzinski, A., D'Orazio, D., Duffell, P., Haiman, Z., MacFadyen, A., MNRAS, 501, 3540, (2021).
- Rubin Observatory will identify 100k's of AGN, so even a "small" binary fraction implies many sources.
- EM identification will be critical for detection and characterization, and potentially needed to measure uncertainties in GW analysis:
  - —> Realistic simulations and their EM output are needed!

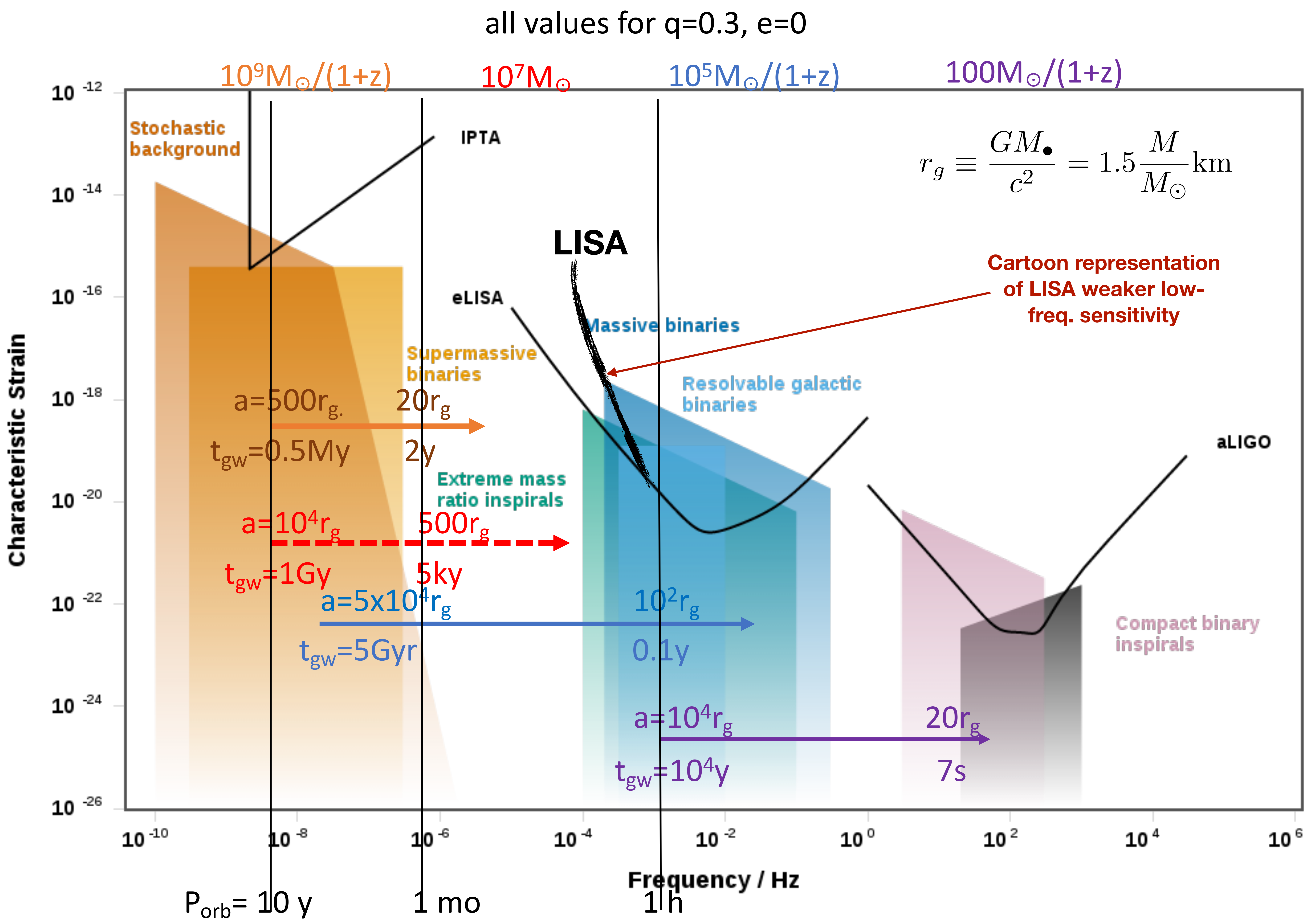


- https://lisa.nasa.gov/

Astrophysics LISA Working Group WP: Amaro-Seoane, Andrews, et al., LISA Consortium Astro Working Group, arXiv, arXiv:2203.06016, (2022).

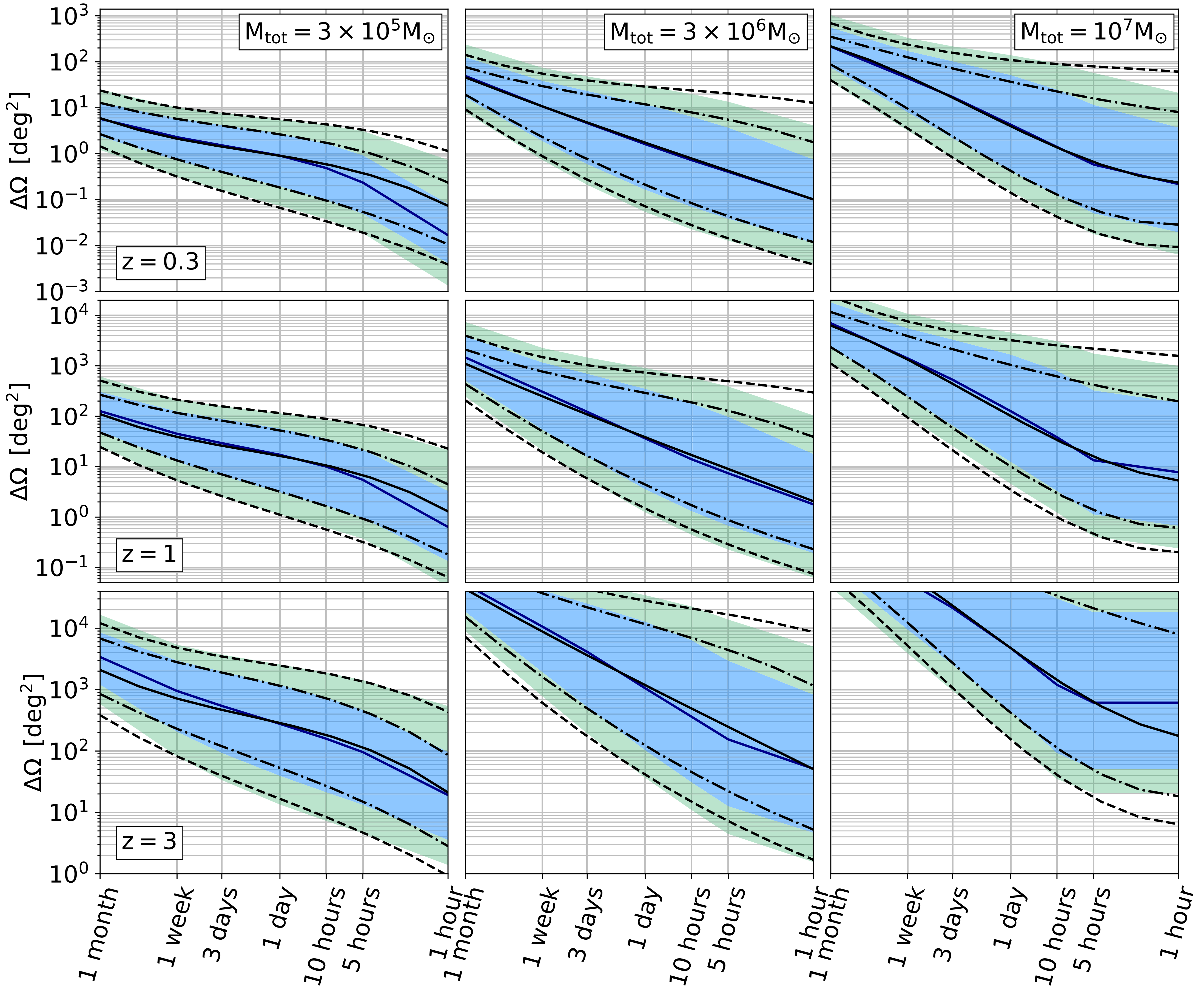
Bogdanović, Miller, and Blecha, LRR, 25, 3, (2022).

Timescale Problem for MMA of Massive Binary Black Holes



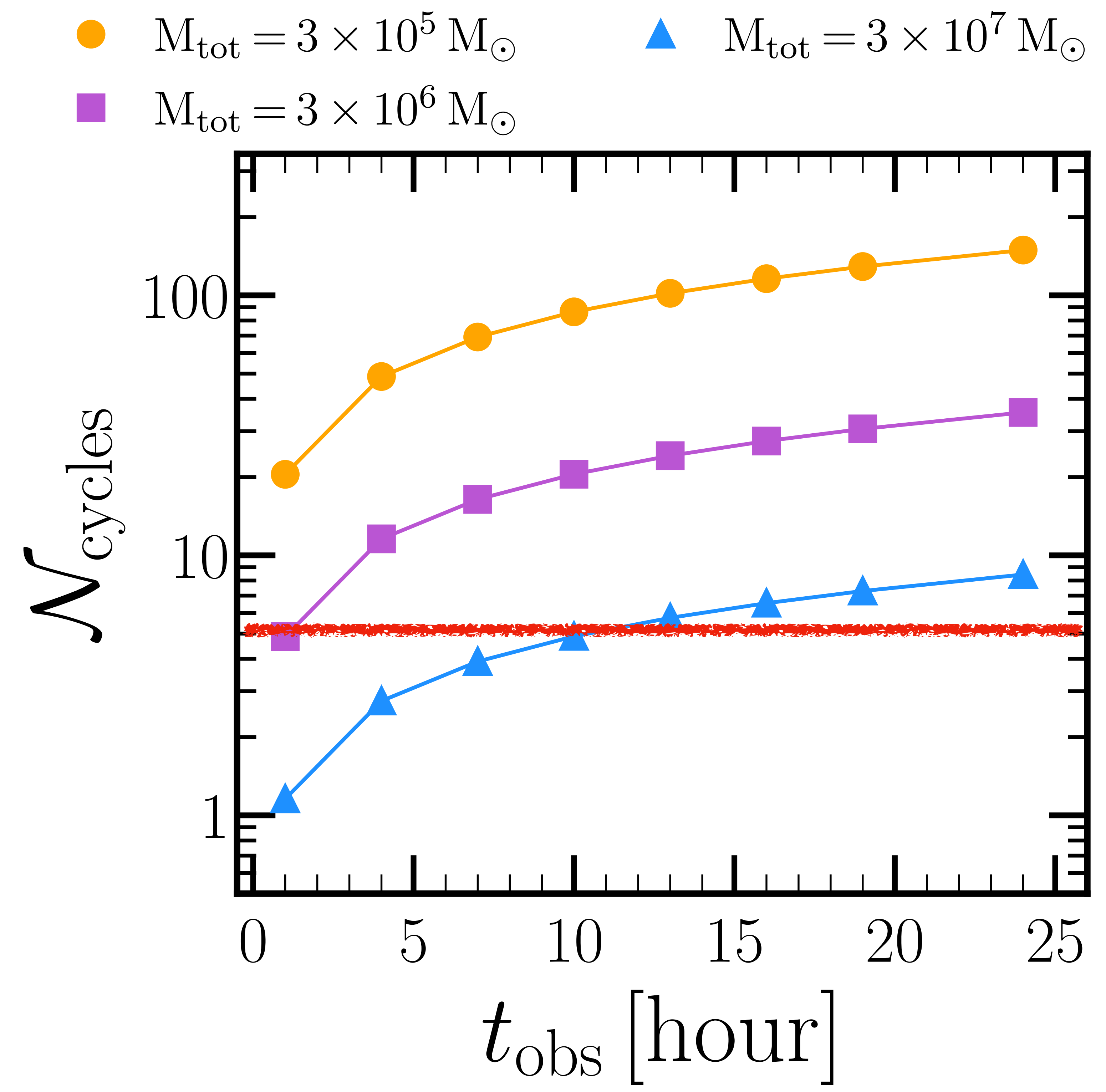
- Class of systems span vast dynamic range in time, from blips to human lifespans;
- What are the best strategies of finding BBH accretors given disparate time scales between dynamics and observational cadences/lifetimes?
- In general for BBHs:
  - PTAs: coherent GW sources that we probably will not see merge;
  - LISA: chirp too fast to localize in time for EM observation, and probably too dim to search sky for before merger;

Catching MBHBs in the Act!



Mangiagli, Klein, Bonetti, Katz, Sesana, Volonteri, Colpi, Marsat, and Babak, PhRvD, 102, 084056, (2020).

Lops, Izquierdo-Villalba, Colpi, Bonoli, Sesana, and Mangiagli, arXiv, arXiv:2207.10683, (2022).



- LISA's angular localization is quickest for lighter MBBHs because of weaker sensitivity at lower frequencies;
- Lighter MBBHs are dimmer in EM, so searches are limited in redshift thus limiting the detectable population.

For PTAs: Goldstein, Sesana, Holgado, and Veitch, MNRAS, 485, 248, (2019).

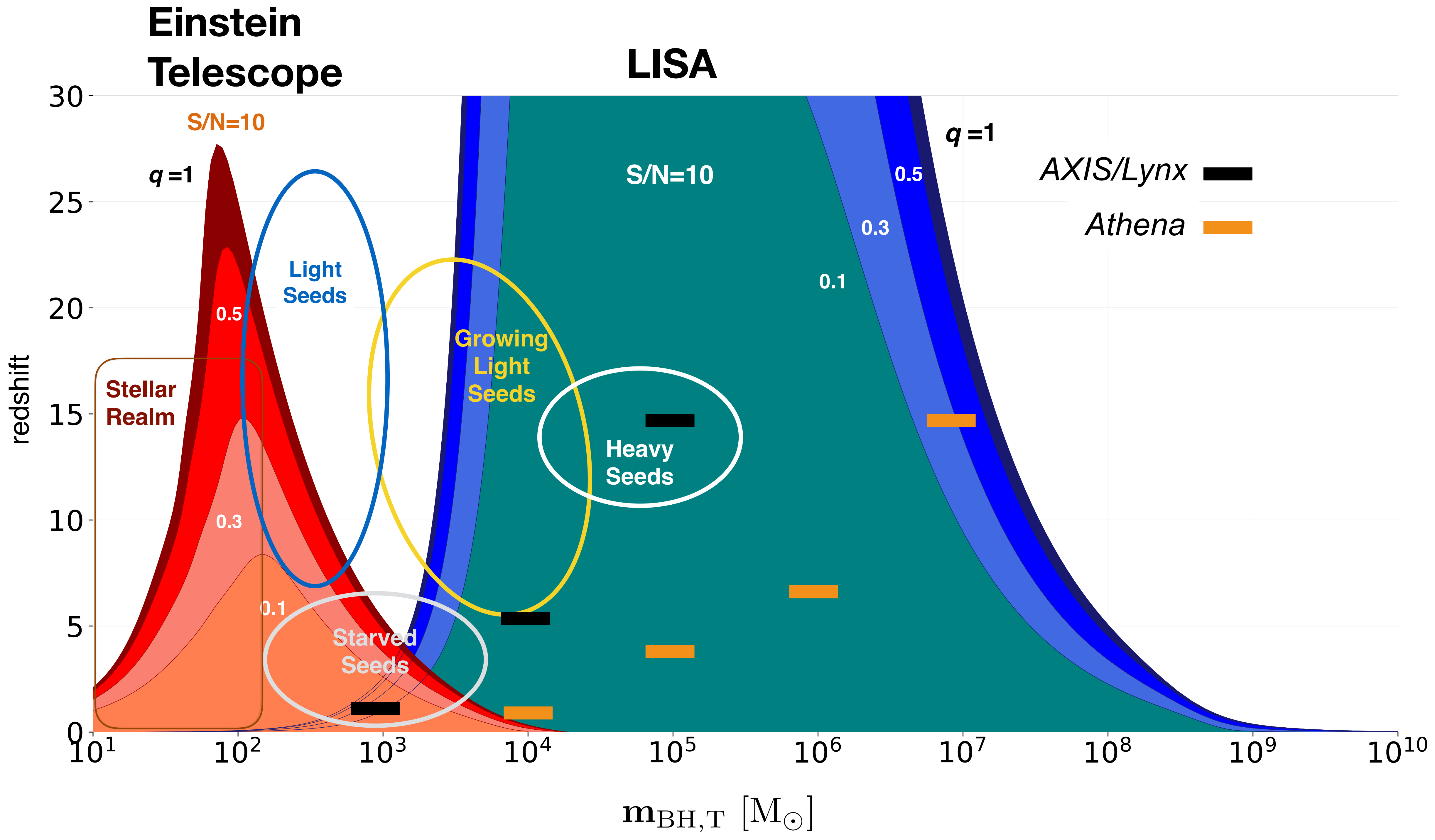
- Effectiveness of inspiral searches increases with :
  - Length of time during which GW/LISA localization is comparable to telescope's FOV or survey-able area;
  - Telescope's FOV, angular resolution, slew rate, and sensitivity;
  - Uniqueness and specificity of binary's EM signature;

Need more & more sophisticated simulations of EM search campaigns, w/wo various mission concepts.

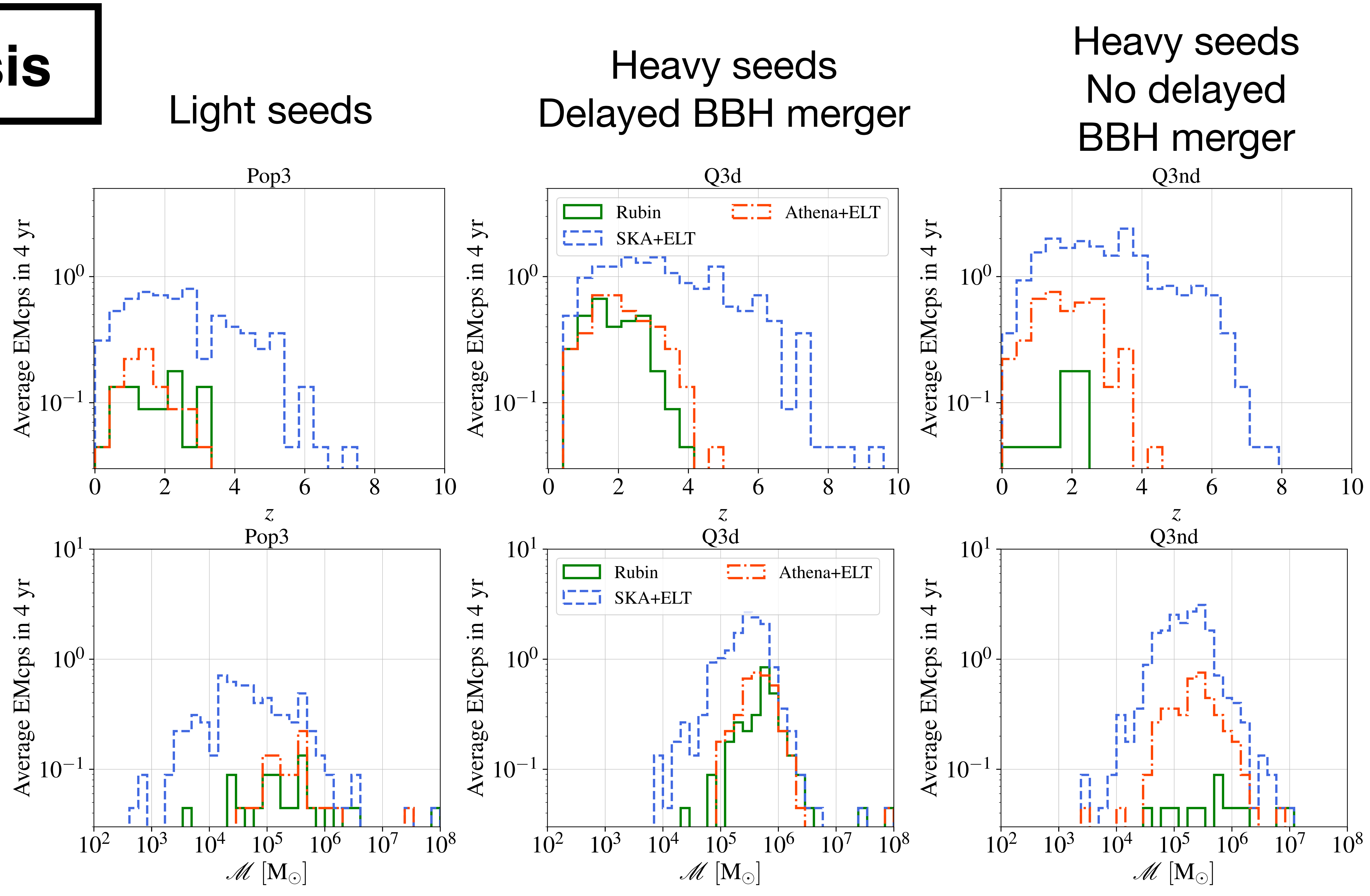
Kelley, Haiman, Sesana, and Hernquist, MNRAS, 485, 1579, (2019).
Dal Canton, Mangiagli, Noble, Schnittman, Ptak, Klein, Sesana, and Camp, ApJ, 886, 146, (2019).

Need realistic predictions (theory) to "match filter" spectral+timing EM data!

Rates & Exploring Population Synthesis



Valiante, Colpi, Schneider, Mangiagli, Bonetti, Cerini, Fairhurst, Haardt, Mills, and Sesana, MNRAS, 500, 4095, (2021).



Mangiagli, Caprini, Volonteri, Marsat, Vergani, Tamanini, and Inchauspé, arXiv, arXiv:2207.10678, (2022).

- Joint X-ray and GW observations could catch seeds of MBH growth in action across time!

7 to 21 (2 to 3) EM+GW Events with 4-yr LISA Campaign

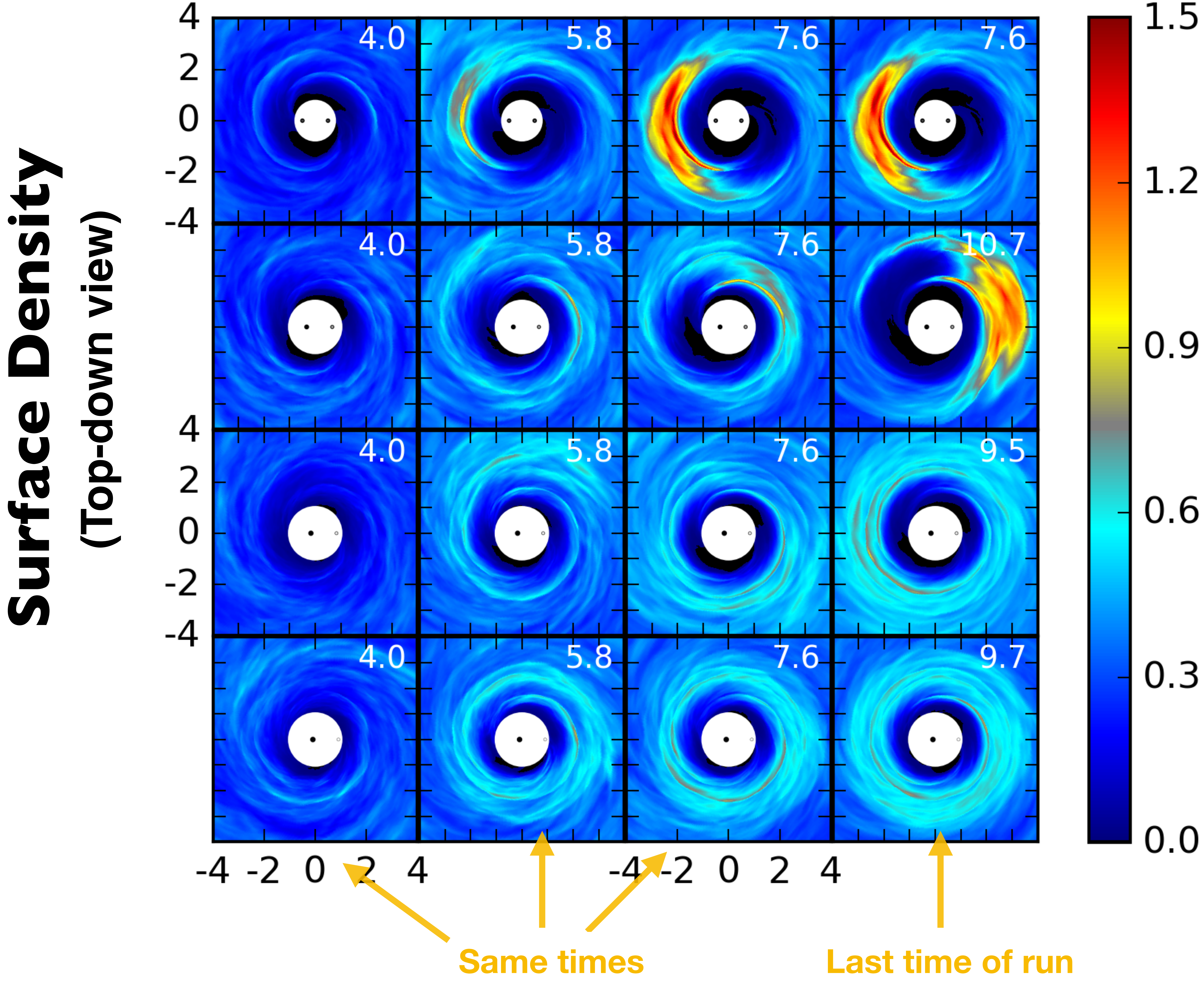
How do these rates change if:

- **surveys/catalogs of MBBH candidates made beforehand?**
- **other observatories are considered (e.g., JWST)?**

- EM Counterpart Searches triggering on GW event, LISA oval fits in FOV of EM observatory;
- Using latest population synthesis models, Eddington luminosities, and observatories’ sensitivities;
- SKA, Athena, Rubin for identification;
- ELT and Rubin for redshift;
- SKA rates (and others too) depend on angular dependence of emission;

Mass Ratio Survey : Circumbinary Disks

Noble, Krolik, Campanelli, Zlochower, Mundim, Nakano, and Zilhão, ApJ, 922, 175, (2021).



$q=M_2/M$

$q=1$

$q=0.5$

$q=0.2$

$q=0.1$

- GRMHD simulations of only circumbinary disk region, starting from Noble++2012 conditions, only changing q.
- As mass-ratio diminishes, so does gravitational torque density of the binary, asymptoting to "single BH" disk;
- Weaker torques (smaller mass ratio binaries) take longer to form lumps.
- Similarities seen with Newtonian results: Shi & Krolik 2016, Munoz+2019, Moody+2019.

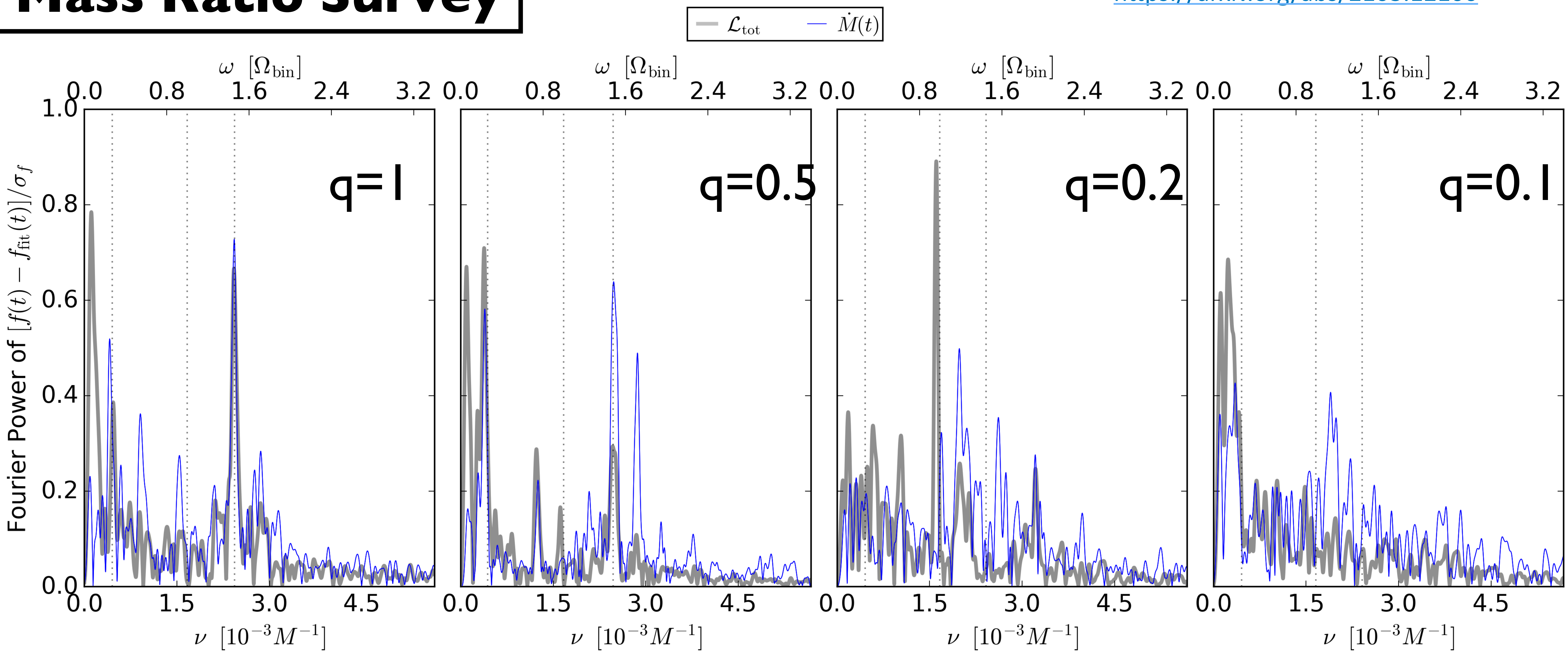
How do we connect the Newtonian scales to the relativistic regime?

Need greater q resolution.

Mass Ratio Survey

Global Trends of the Lump

Noble, Krolik, Campanelli, Zlochower, Mundim, Nakano, Zilhao (2021)
https://arxiv.org/abs/2103.12100



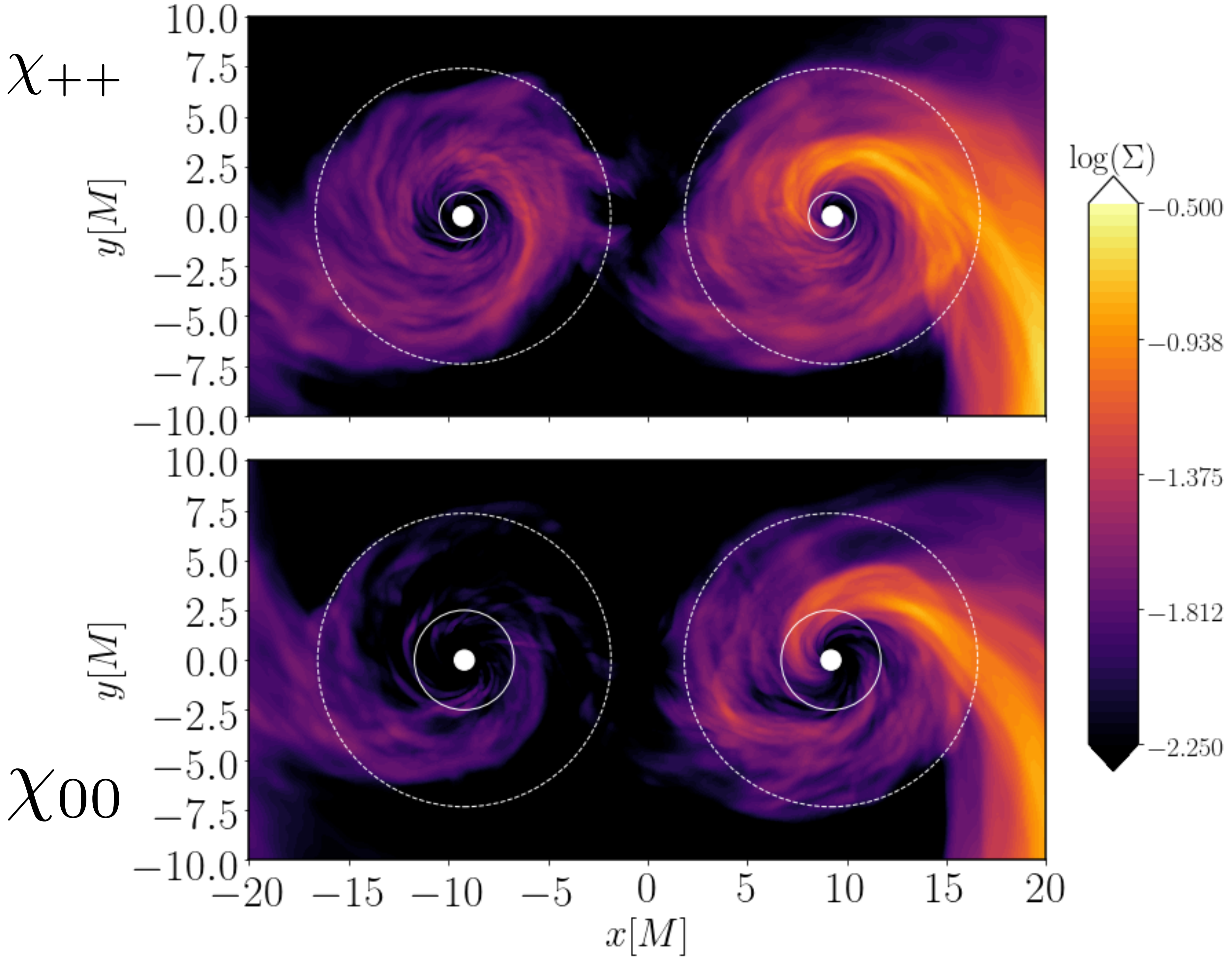
- **Non-trivial signals apparent in L(t) and Mdot(t) at** $2\Omega_{\rm beat}$
- **Signals in accretion rate and luminosity are not always shared;**
- **Small-q binaries show red-noise dominated power spectrum like single-BH disks;**
- **Intermediate-q binary shows strongest signal at binary frequency, as the disk interacts primarily with BH#2;**
- **Mdot modulations modulate mini-disk luminosities, which are brightest high-energy component;**

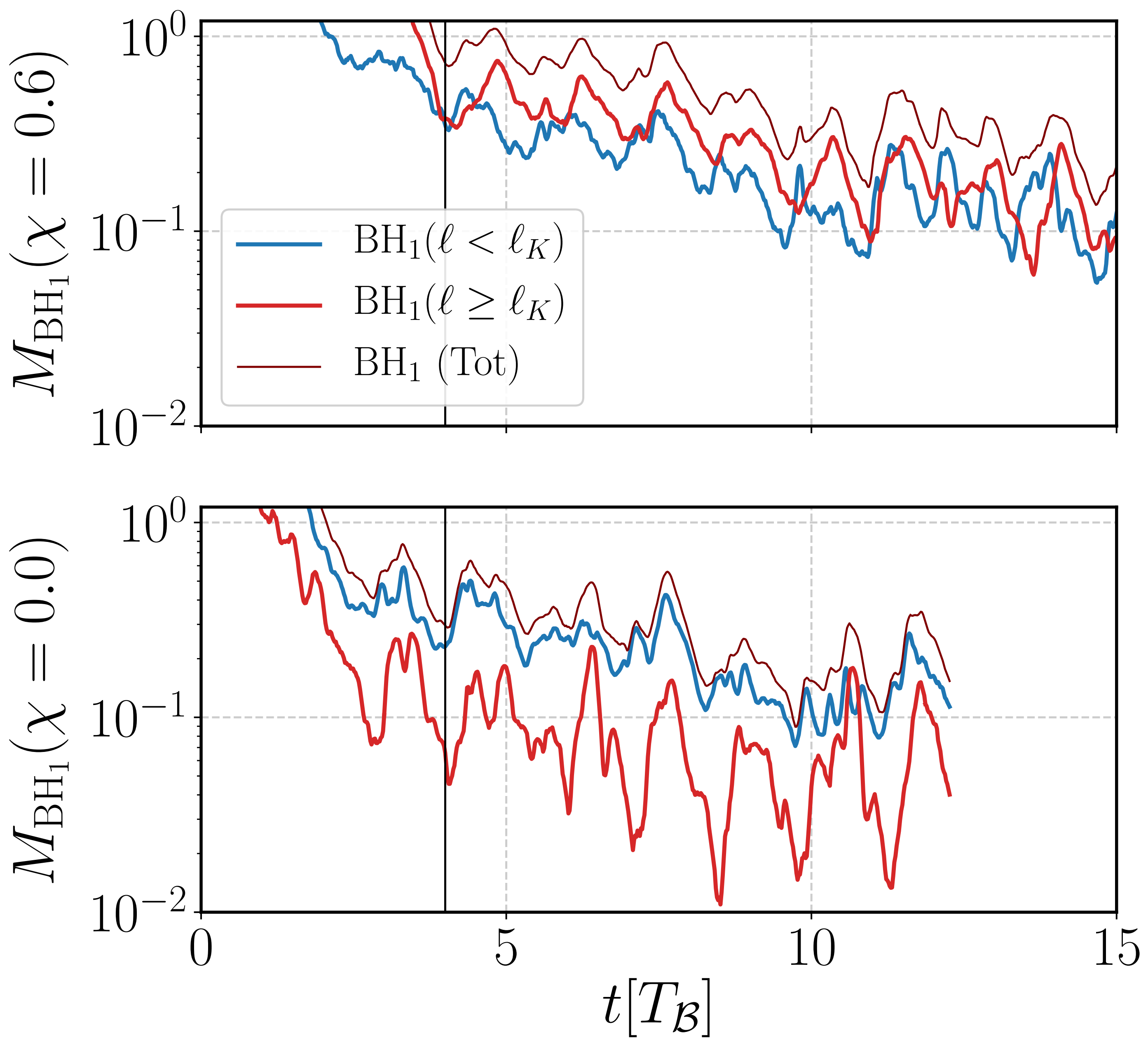
Nonlinear dynamics means we need simulations — cannot be done with analytic theory!

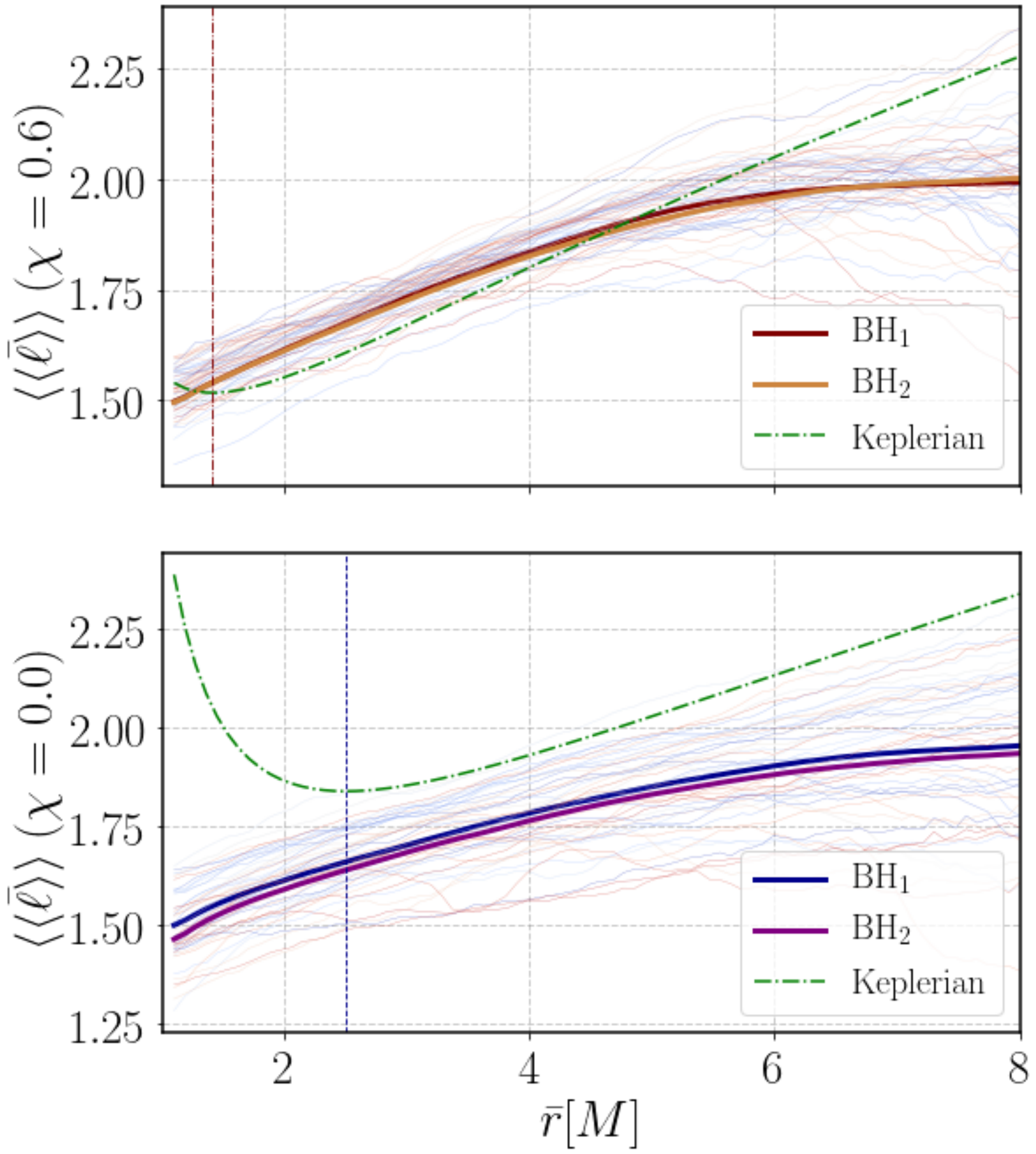
Accretion onto Spinning BBHs

Circumbinary + Mini- Disk Regions

Combi, Lopez Armengol, Campanelli, Noble, Avara, Krolik, and Bowen, ApJ, 928, 187, (2022).







$$\chi = +0.6$$

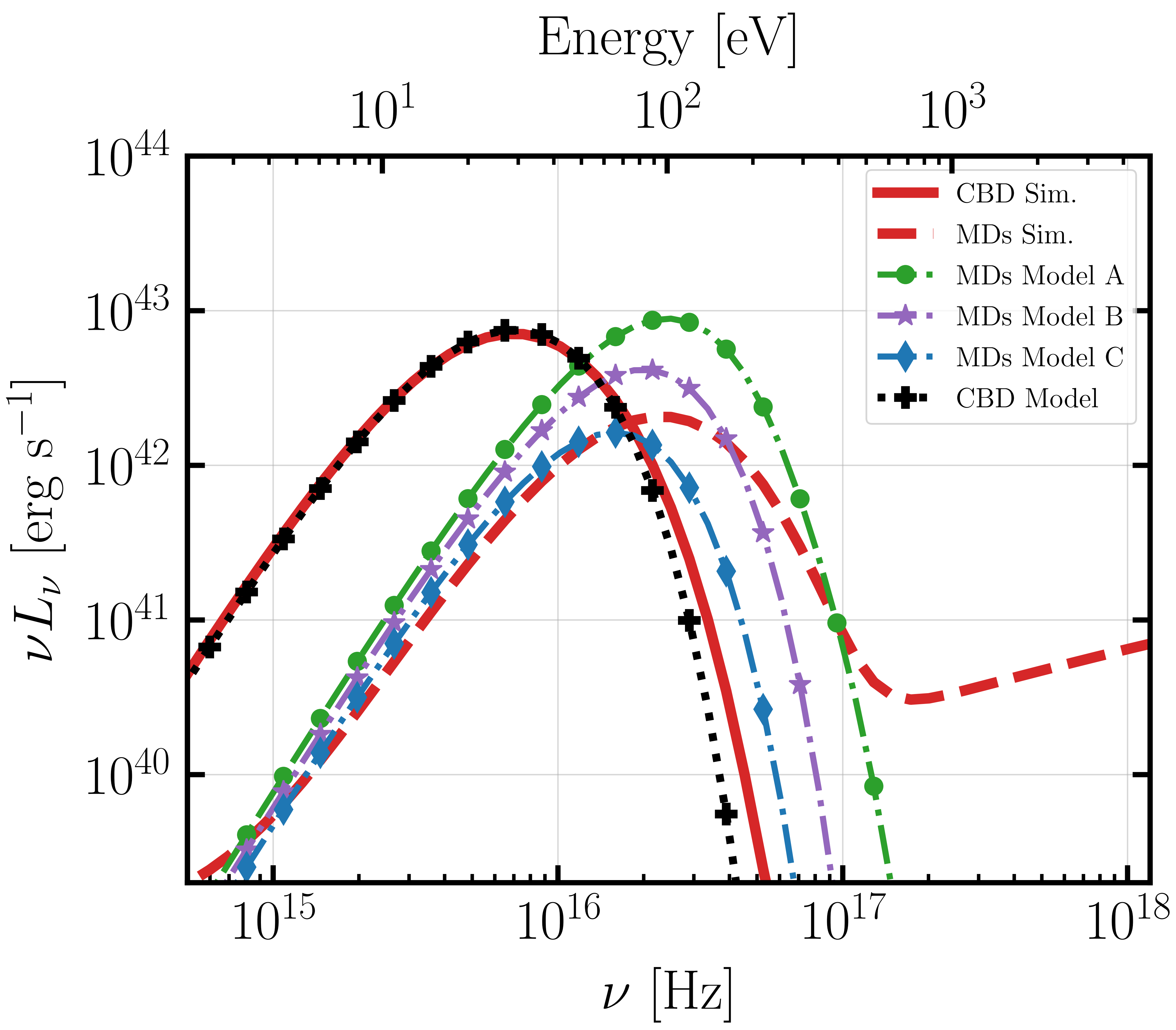
- **Starting from same initial accretion flow conditions;**
- **Because of smaller ISCO, the volume of stability in mini-disk region increases for larger (parallel) spin;**
  - **—>More persistent mini-disks;**
  - **—> Longer inflow time scales;**
  - **—> Comparable accretion rates;**
  - **—> Smaller fluctuations at 2x beat freq.**

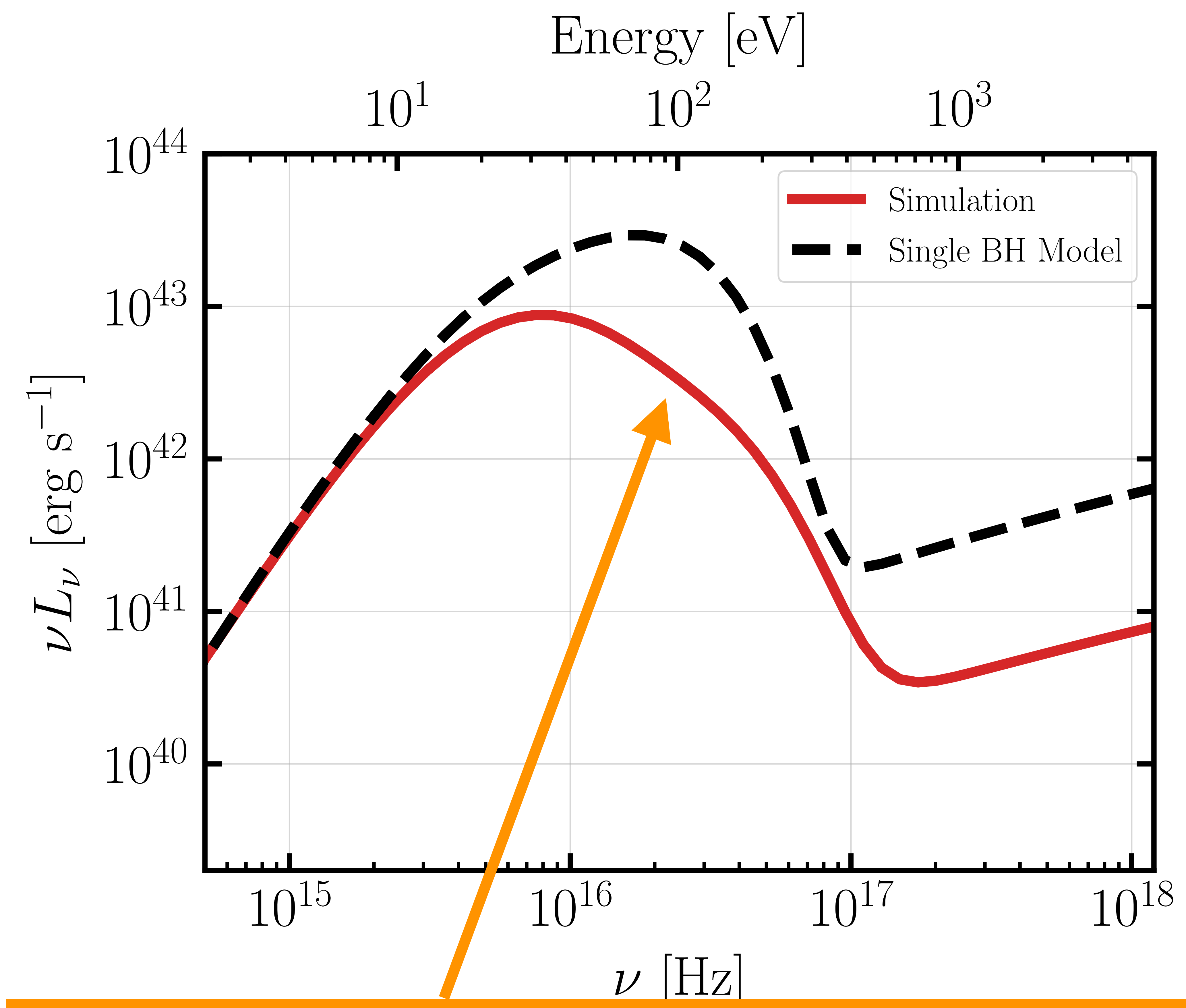
- **Faster spins change the potential so that the accretion streams are no longer sub-Keplerian, allowing for gas to accumulate;**
- **Mini-disks are 2x as massive with spins than without.**

Need to explore more spins and disk properties (accretion rate).

Spectra from Accretion onto Spinning BBHs

Gutiérrez, Combi, Noble, Campanelli, Krolik, López Armengol, and García, ApJ, 928, 137, (2022).





Spinning BBHs

Schnittman, Krolik, and Noble, ApJ, 819, 48, (2016).

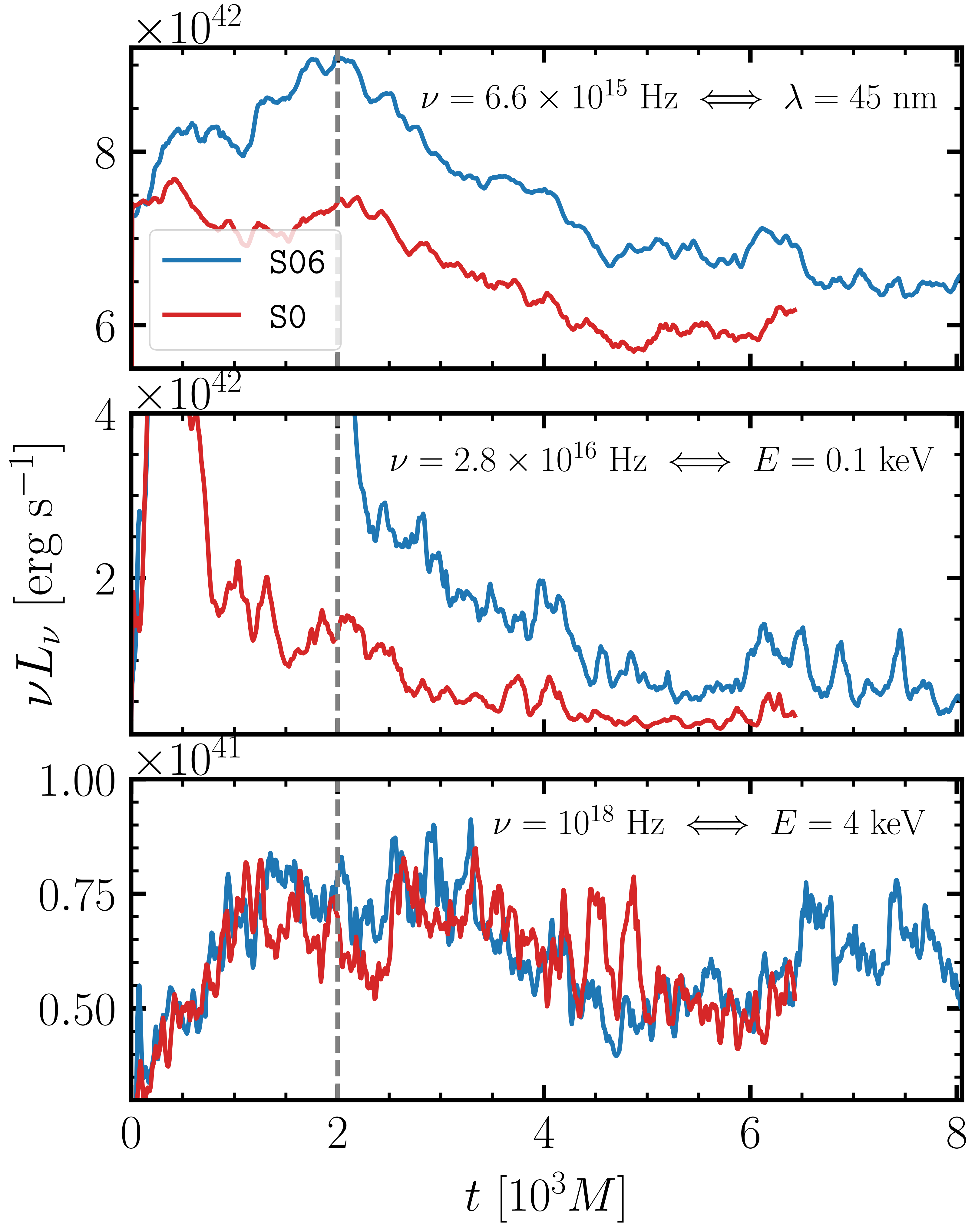
- GRMHD simulation-informed model for all spins for thin disks, same total mass and Mdot;
- Truncated disk emission, weaker mini-disk accretion rate due to accelerated accretion via shocks.

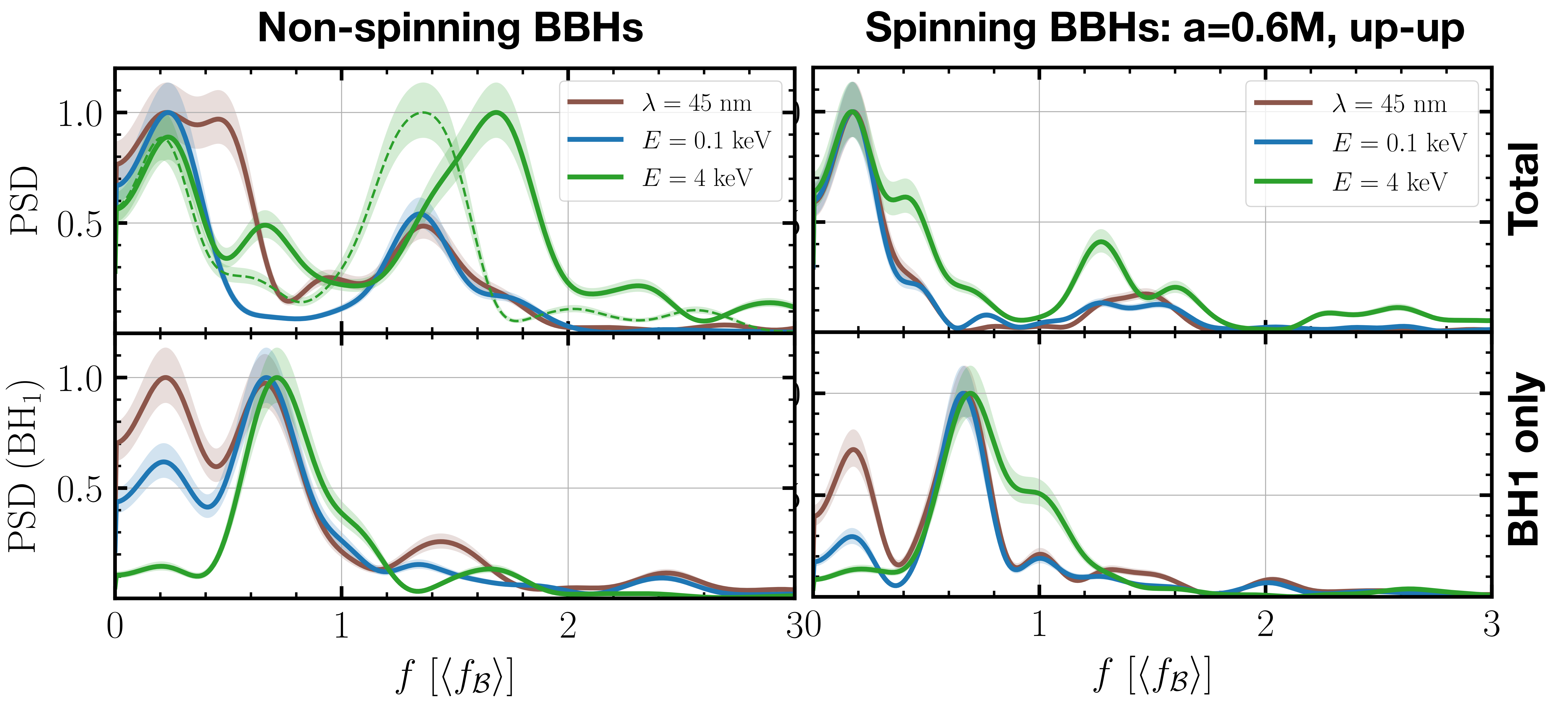
How does the predicted dip in the UV change with binary separation? Does it become more significant at larger separations? Roedig, Krolik, and Miller, ApJ, 785, 115, (2014).

Need more realistic corona, high-energy radiation methods, and radiation coupling to explore accretion stream physics.

Light Curves from Accretion onto Spinning BBHs

Gutiérrez, Combi, Noble, Campanelli, Krolik, López Armengol, and García, ApJ, 928, 137, (2022).





Need additional thermodynamics to include hard X-ray emission from accretion stream shock!

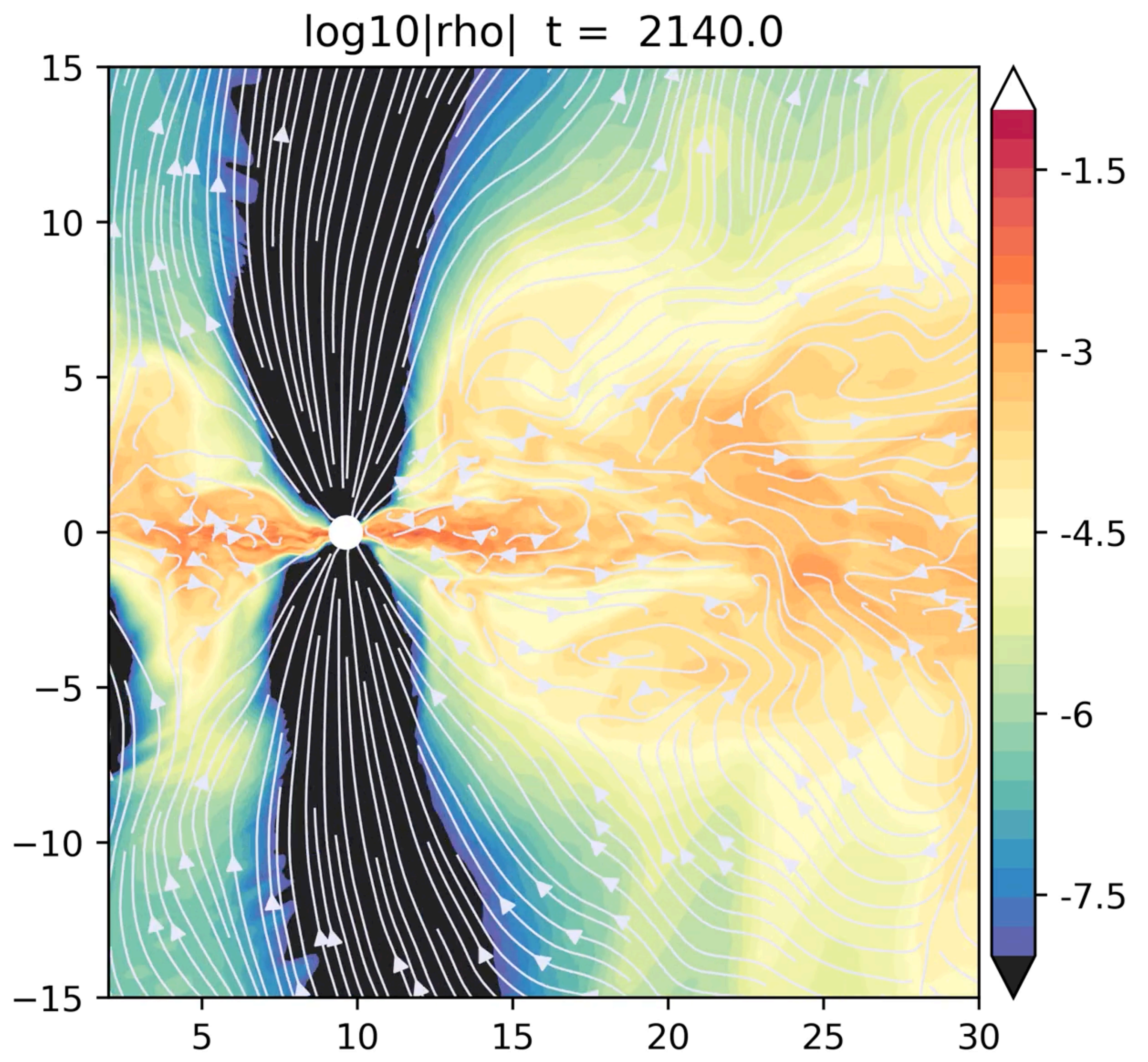
Roedig, Krolik, and Miller, ApJ, 785, 115, (2014).

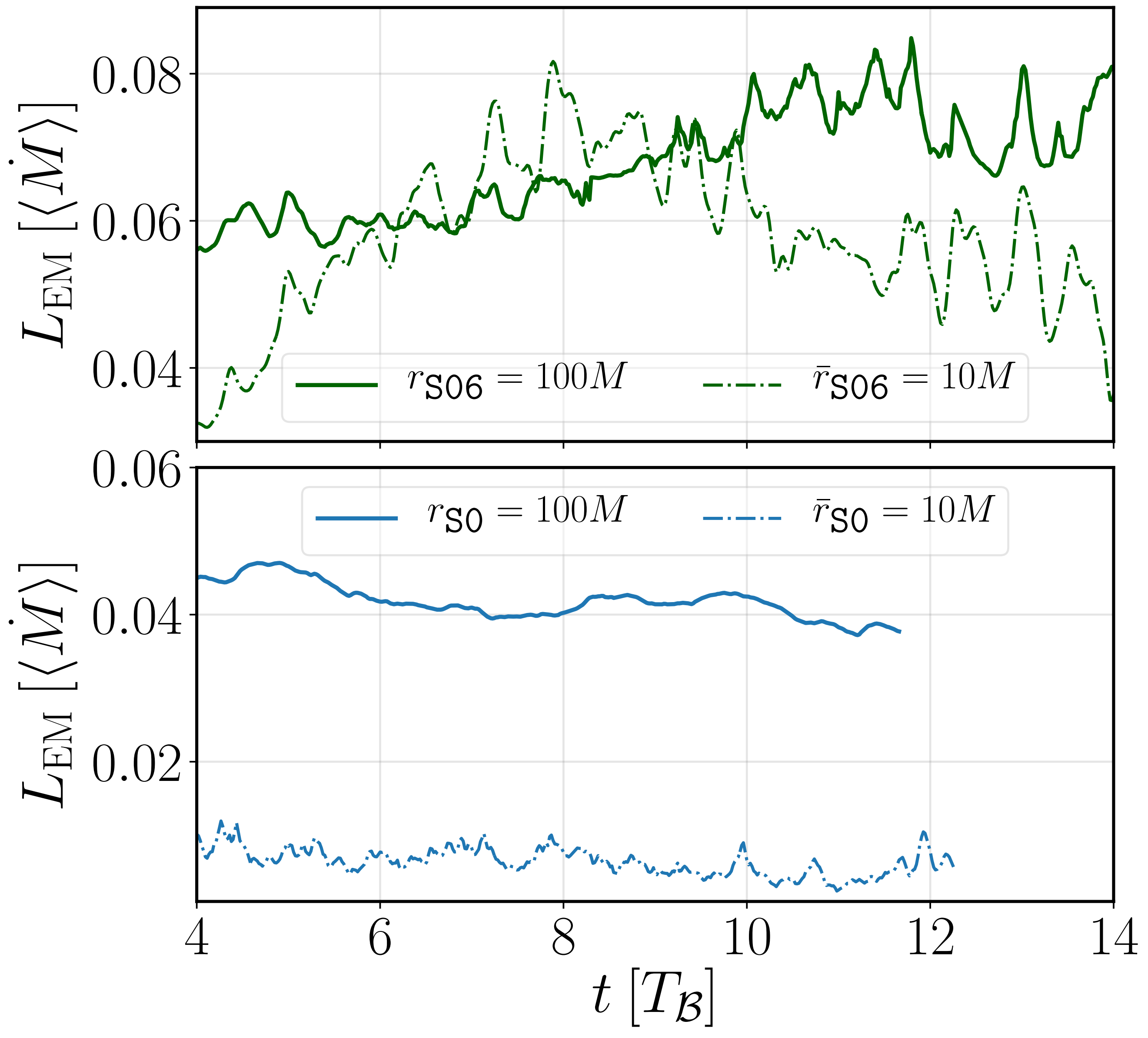
- Prograde spinning BBHs:
  - Longer-lived mini-disks lead to relatively steadier x-ray emission and weaker signals at 2x beat freq.;
  - Individual mini-disks still suffer beat modulation;
- Presence and ratios of PSD peaks could be used to identify source as a binary and whether they are spinning;
- Predict spinning BBHs will be predominantly varying at lower-frequencies than gravitational waves;

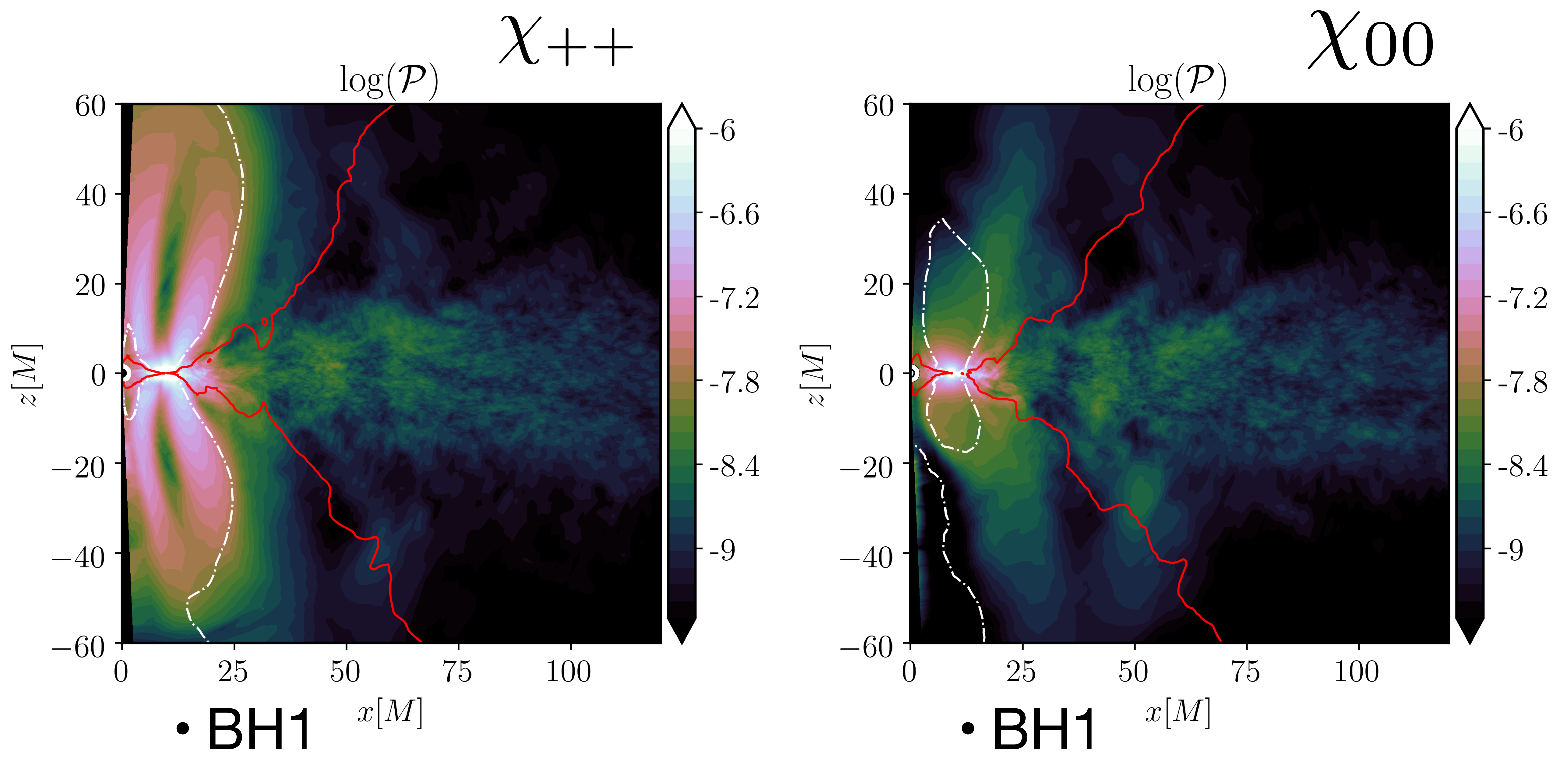
Poynting Flux from BBHs

Circumbinary + Mini- Disk Regions

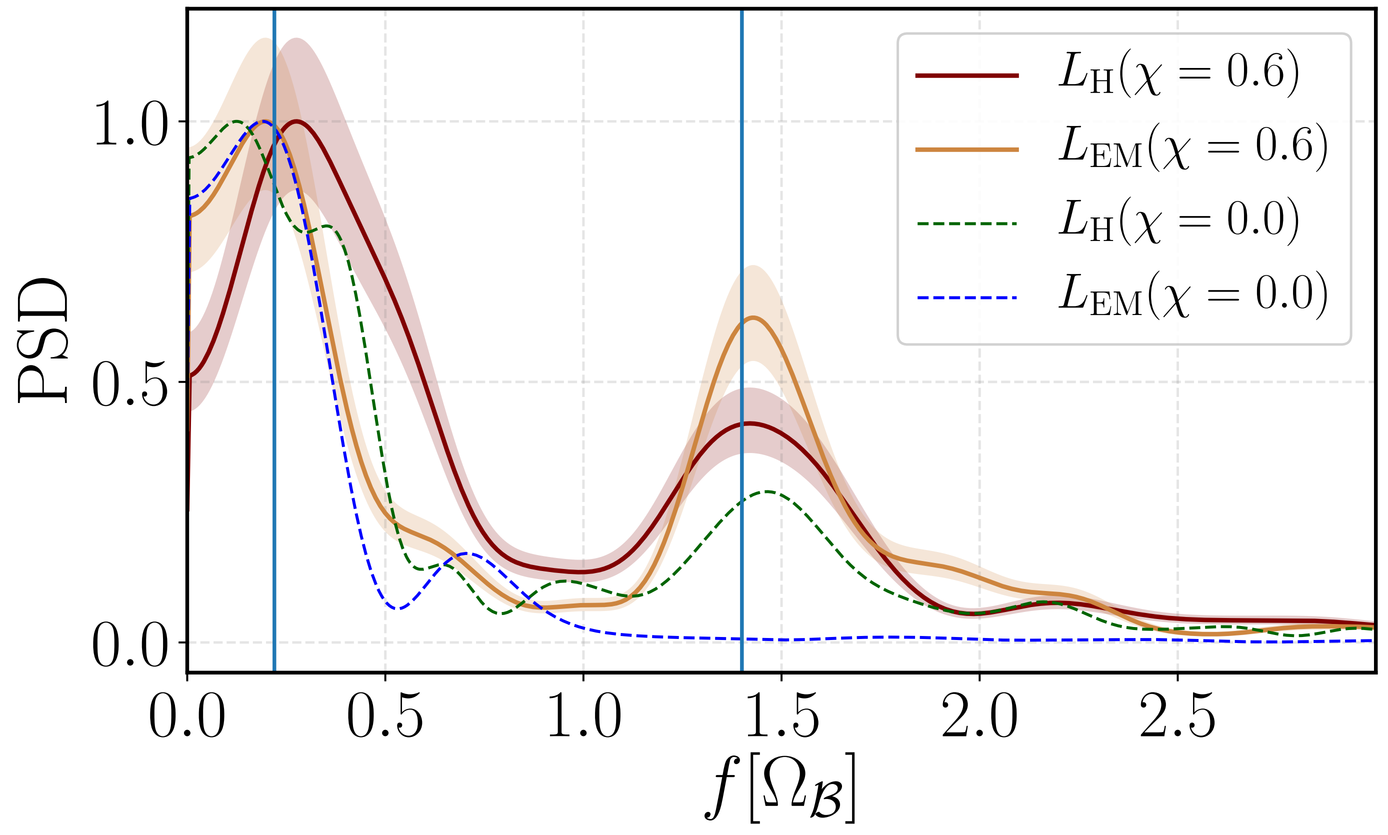
Poynting Scalar







- Funnel region is more magnetized with spins.



- **Hydro and EM fluxes are both larger with spins;**
  - **Possible signature of helical field orientation in emission's polarization?!**
- **Poynting luminosity modulated at 2x beat freq. w/ lump;**

How do other spin values and spin orientations change this picture?

Combi, Lopez Armengol, Campanelli, Noble, Avara, Krolik, and Bowen, ApJ, 928, 187, (2022).

	χ_{00}	χ_{++}
$\eta_{\rm EM}$	0.5% —> 4%	7.5%
$\eta_{\rm H}$	2.5%	10%

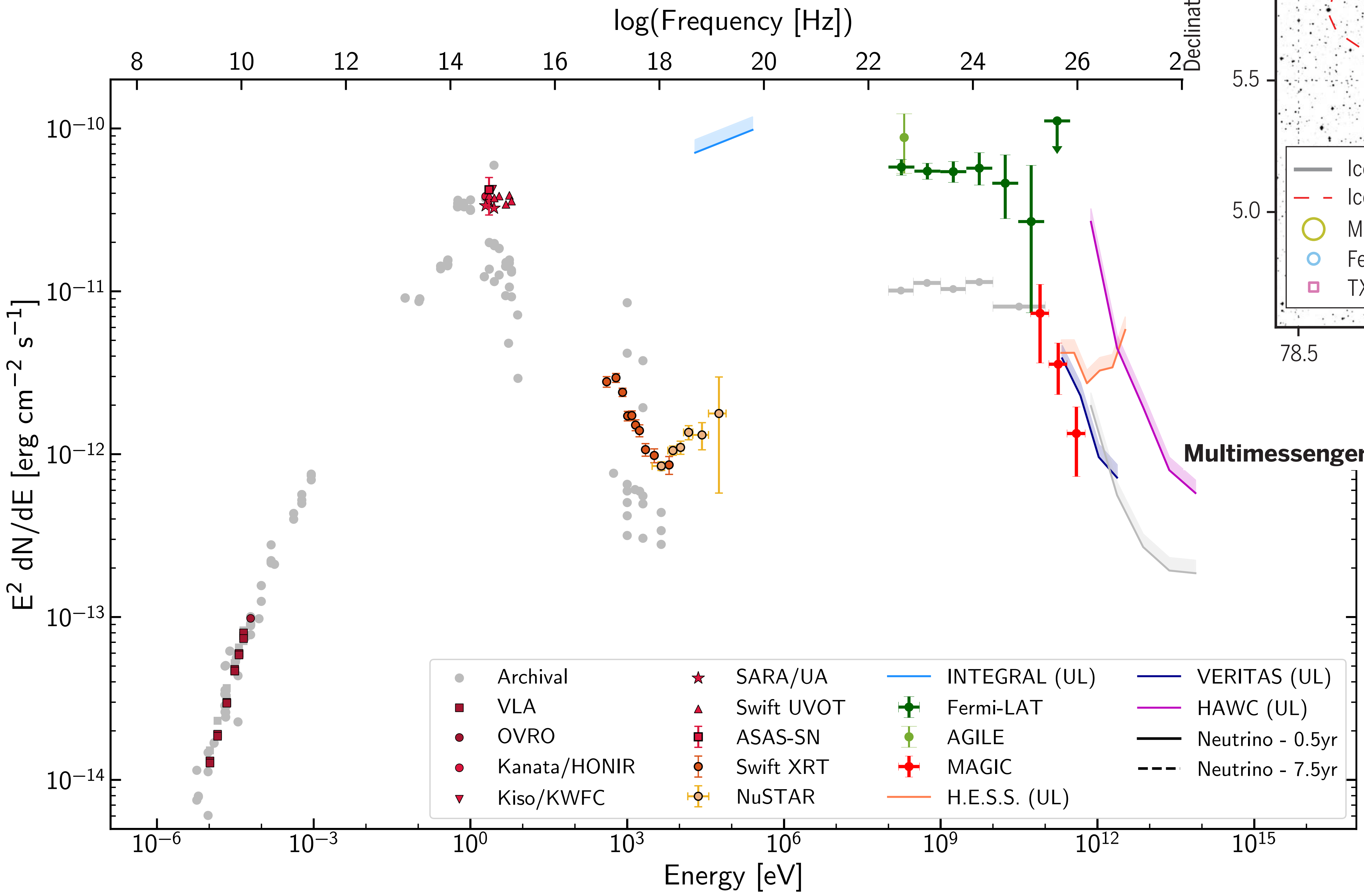
Simultaneous Images of Synchrotron Jets and Optically Thin X-ray Emission

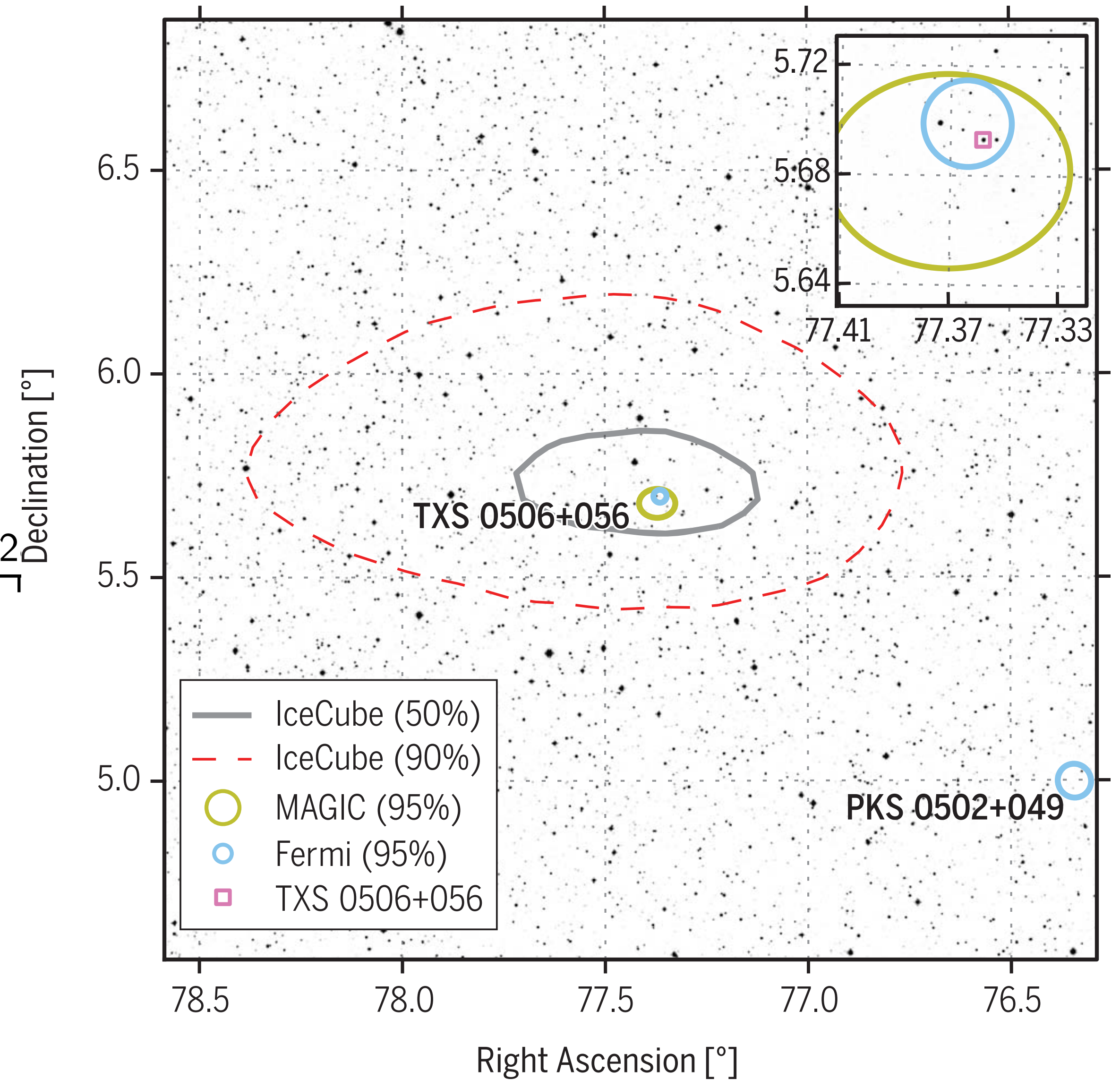
- Gutierrez, Combi, Lopez Armengol++(in prep)
- Dual jet phenomena;
- Synchrotron calculated using same emissivities used in simulations of images for the Event Horizon Telescope project. Leung, Gammie, and Noble, ApJ, 737, 21, (2011).
- Predict correlated X-ray and jet variability, under certain situations, TBD.

NEUTRINO ASTROPHYSICS

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†





Multimessenger observations of blazar TXS 0506+056. The

Jets from MBBHs: Potential 3-messenger source!

Can blazers be binaries (e.g., OJ 287)?
Are jets in binaries common?
Do they accelerate cosmic rays in the same way?

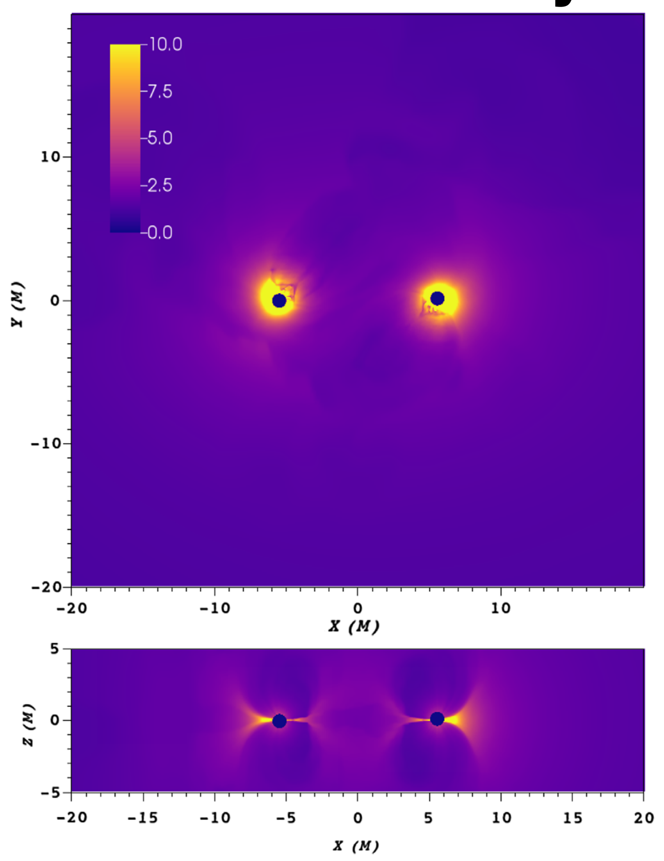
Merger Signatures

Numerical Relativity with Uniform Plasmas

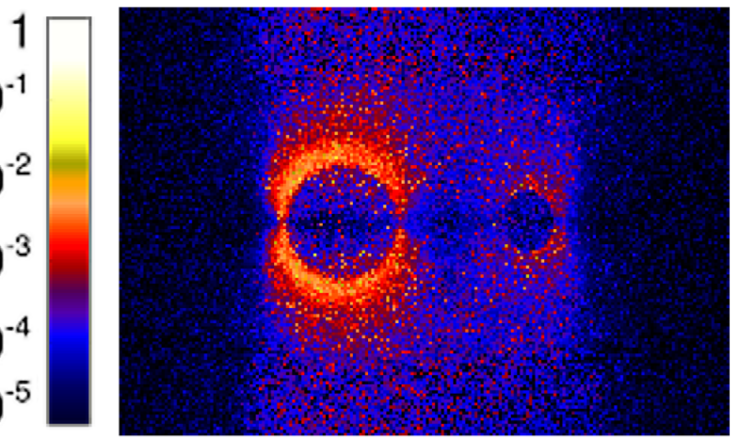
Prior Art:

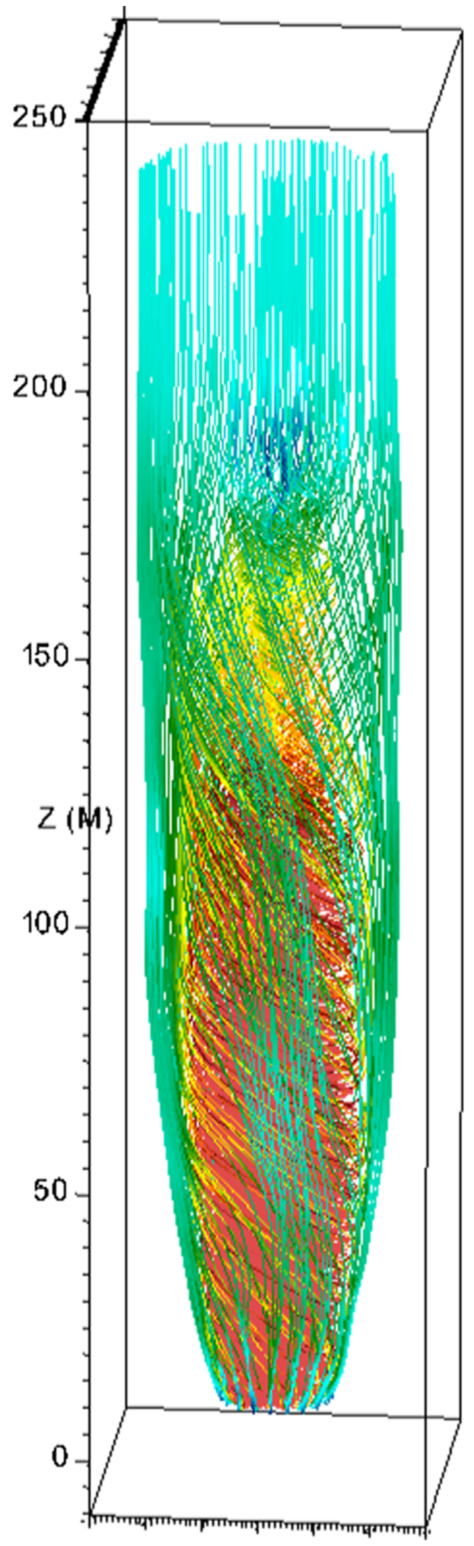
- Palenzuela, Garrett, Lehner, and Liebling, PhRvD, 82, 044045, (2010), Moesta, Alic, Rezzolla, Zanotti, and Palenzuela, ApJL, 749, L32, (2012).

Plasma Density

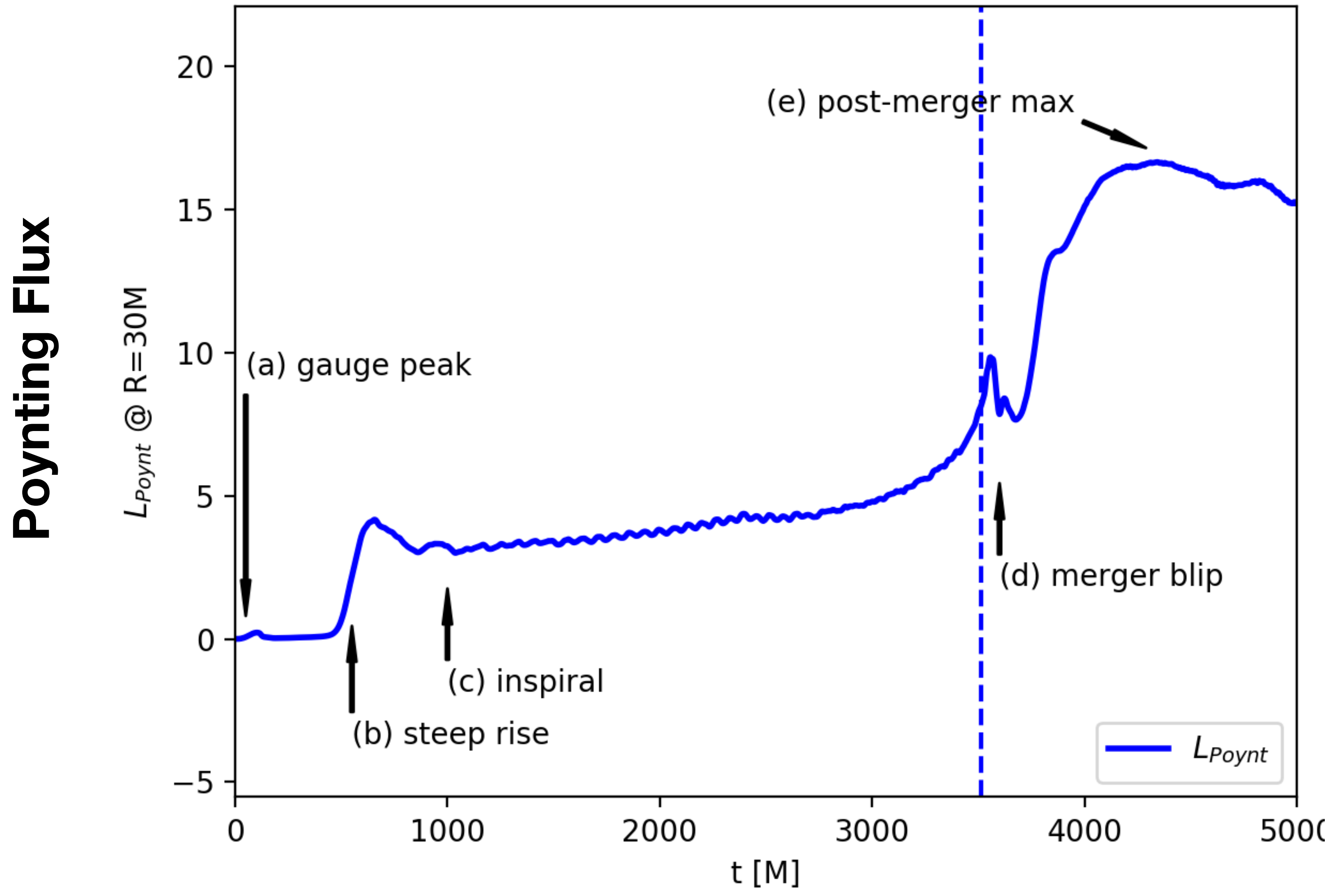


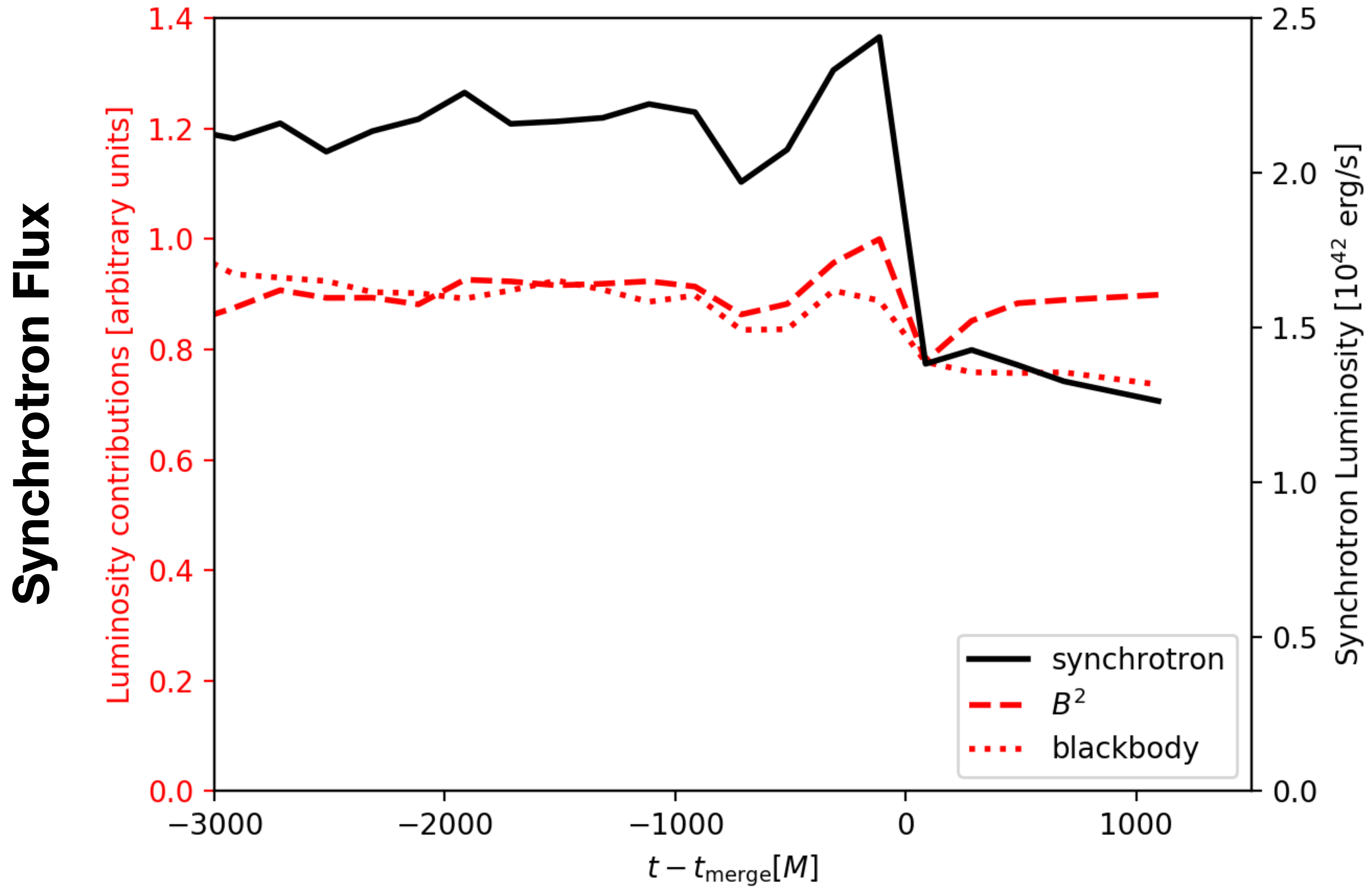
Synchrotron Image





- **B-field**
- **Lines**





How does Poynting flux turn into observables we will actually see?

How do merger/post-merger predictions change with initial data predicted from pre-merger simulations?

Without spins: Kelly, Baker, Etienne, Giacomazzo, Schnittman, PRD 96, 123003 (2017)

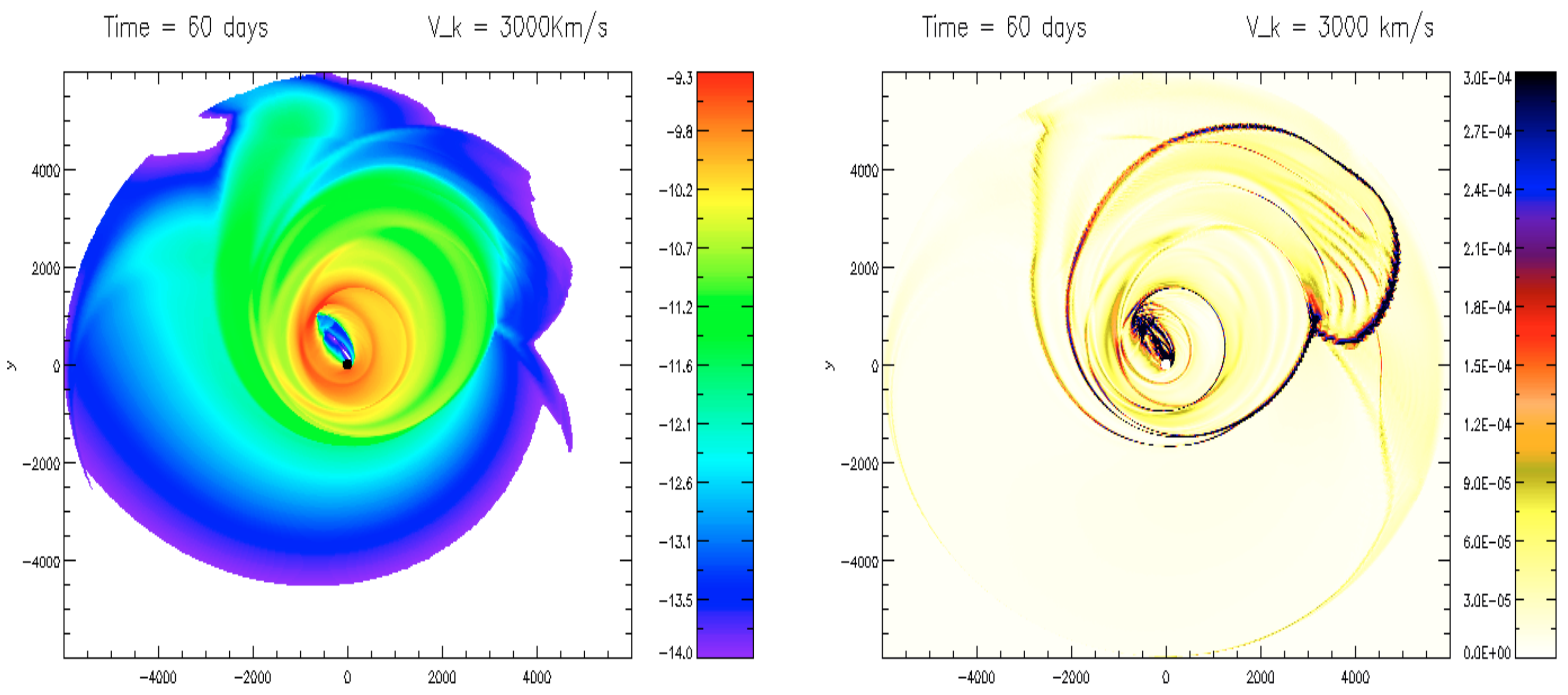
With spins: Cattorini, Giacomazzo, Haardt, and Colpi, PhRvD, 103, 103022, (2021).

- Poynting flux grows in time, reaching maximum post-merger; Synchrotron plunges at merger;
- Spins increase Poynting flux luminosities;

What about particle acceleration, both gravitational and via internal shocks?

Post-merger Aftermath: Kicks, Mass Loss, Jets

Numerical Relativity + MHD Evolutions



Zanotti, Rezzolla, Del Zanna, and Palenzuela, A&A, 523, A8, (2010).

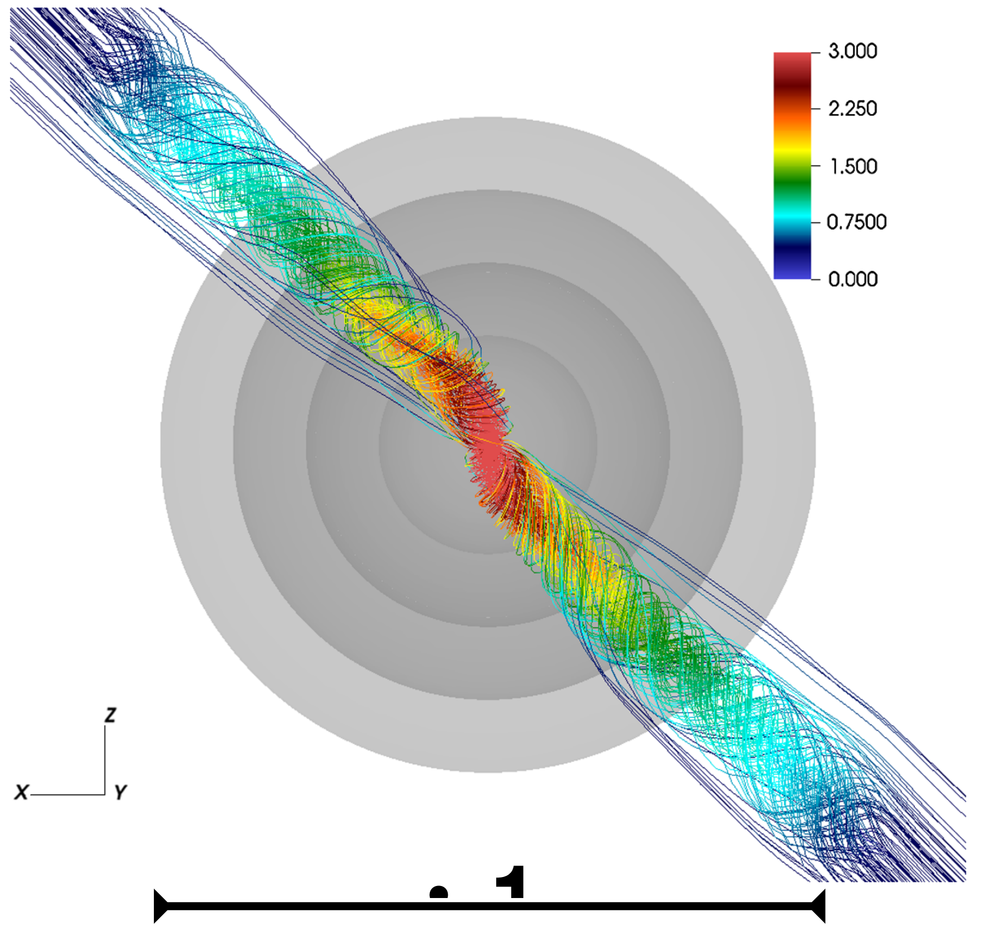
- BBH merger leads to O(100) km/s kicks on merger remnant and few-several % mass loss due to GW losses;
- Disk “adjusts” or is “kicked” by the sudden change in the gravity, often triggering eccentric shocks that dissipate change motion triggered by change in potential energy;
- Observables are often significant tens-hundreds of days post-merger for massive BBHs.

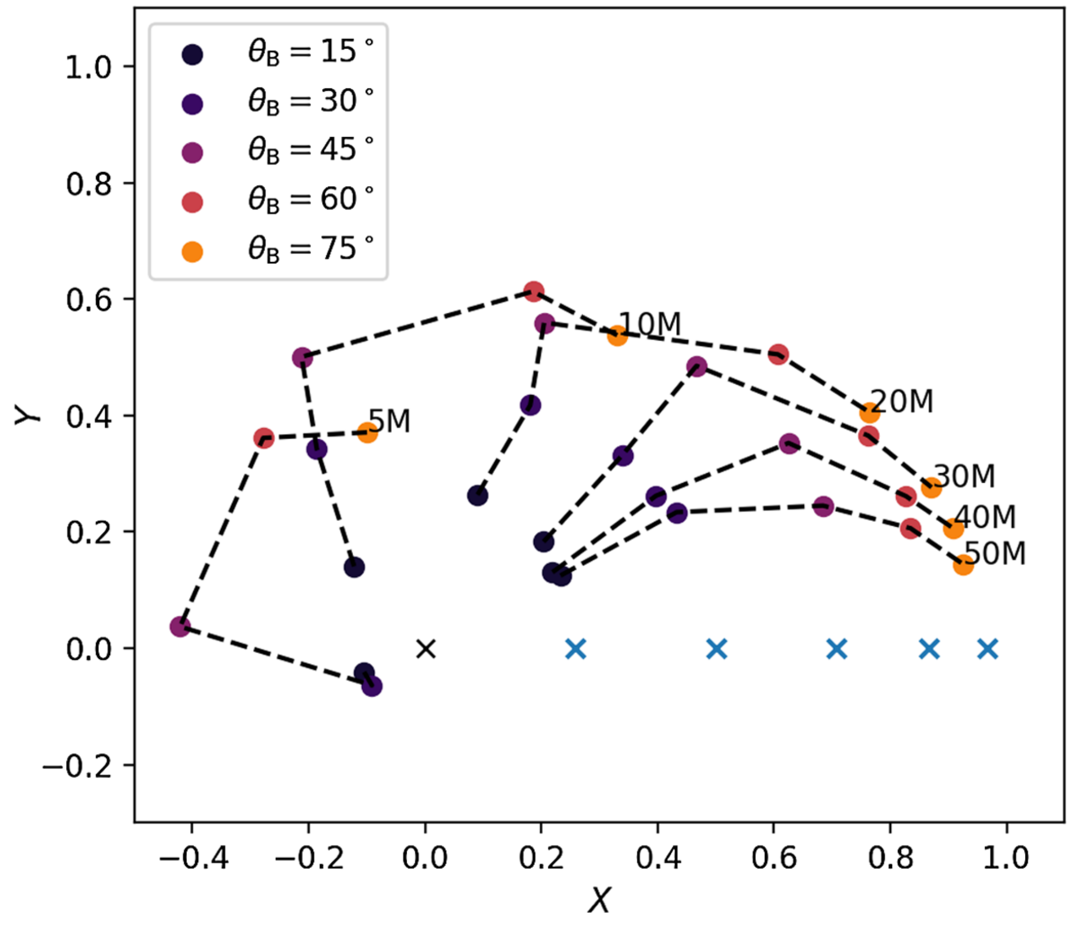
What are the prospects for seeing kicks in the JWST era? What other instruments are needed to search for them? Will Rubin aid in their search?

- Kelly, Etienne, Golomb, Schnittman, Baker, Noble, Ryan, PRD 103, 063039 (2021)

- Spinning post-merger single BHs, Uniform plasma;
- Survey over angle between B-field and spin;
- Survey over temperature;

⭐Jet starts aligned with spin, then aligns with B-field;
⭐Poynting luminosity strongest when aligned;





Possible reason for X-shaped radio lobes

How do merger/post-merger predictions change with initial data predicted from pre-merger simulations?

Future Work & Recommendations

What about particle acceleration, both gravitational and via internal shocks?

Need realistic predictions (theory) to “match filter” spectral+timing EM data!

How does Poynting flux turn into observables we will actually see?

How do merger/post-merger predictions change with initial data predicted from pre-merger simulations?

How does the predicted dip in the UV change with binary separation? Does it become more significant at larger separations?

Need more realistic corona, high-energy radiation methods, and radiation coupling to explore accretion stream physics.

How do we connect the Newtonian scales to the relativistic regime?

How do other spin values and spin orientations change this picture?

Additional thermodynamics to include hard X-ray emission from accretion stream shock!

Need additional theory and computational support, as recommended by decadal:

- **ATP to 1 cycle per year;**
- **Stronger/stabler TCAN program;**
- **Additional funds;**

More exploration of EM searches to evaluate performance of future missions, and identify and fill gaps in spectral/timing.

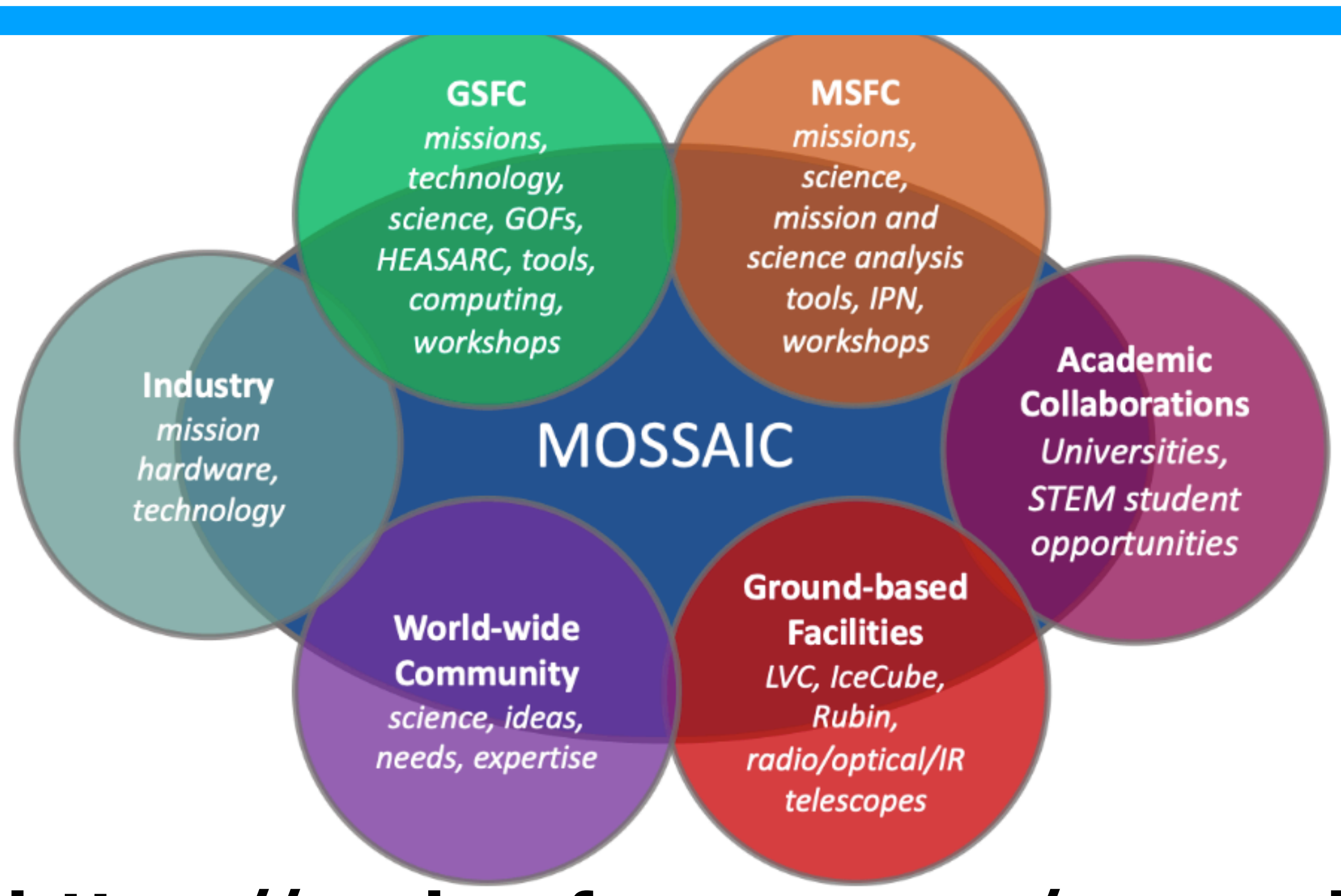
What is the “optimal” combination of observatories and search strategies?

How do these rates change if:

- surveys/catalogs of MBBH candidates made beforehand?
- other observatories are considered (e.g., JWST)?

More & more sophisticated simulations of EM search campaigns, w/wo various mission concepts.

Ideally, watch “Everything Everywhere all at Once”, but can save budget by focusing on deep all-sky X-ray, , UV—>IR, and radio surveys.



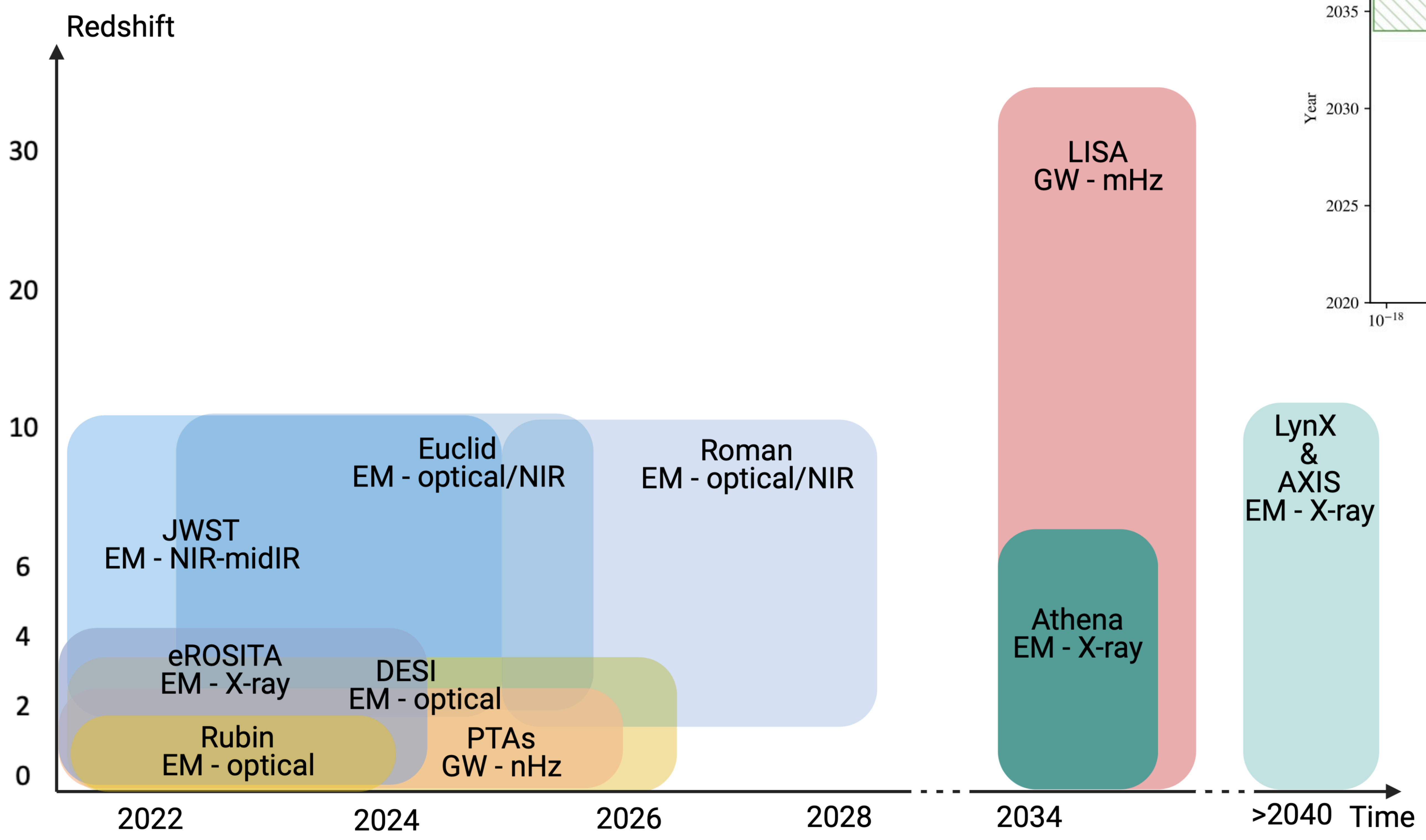
Coordination of facilities, archives, modelrto enable quick capture of merging systems, and also long-term multi-wavelength follow-up for the “continuous” PTA sources.

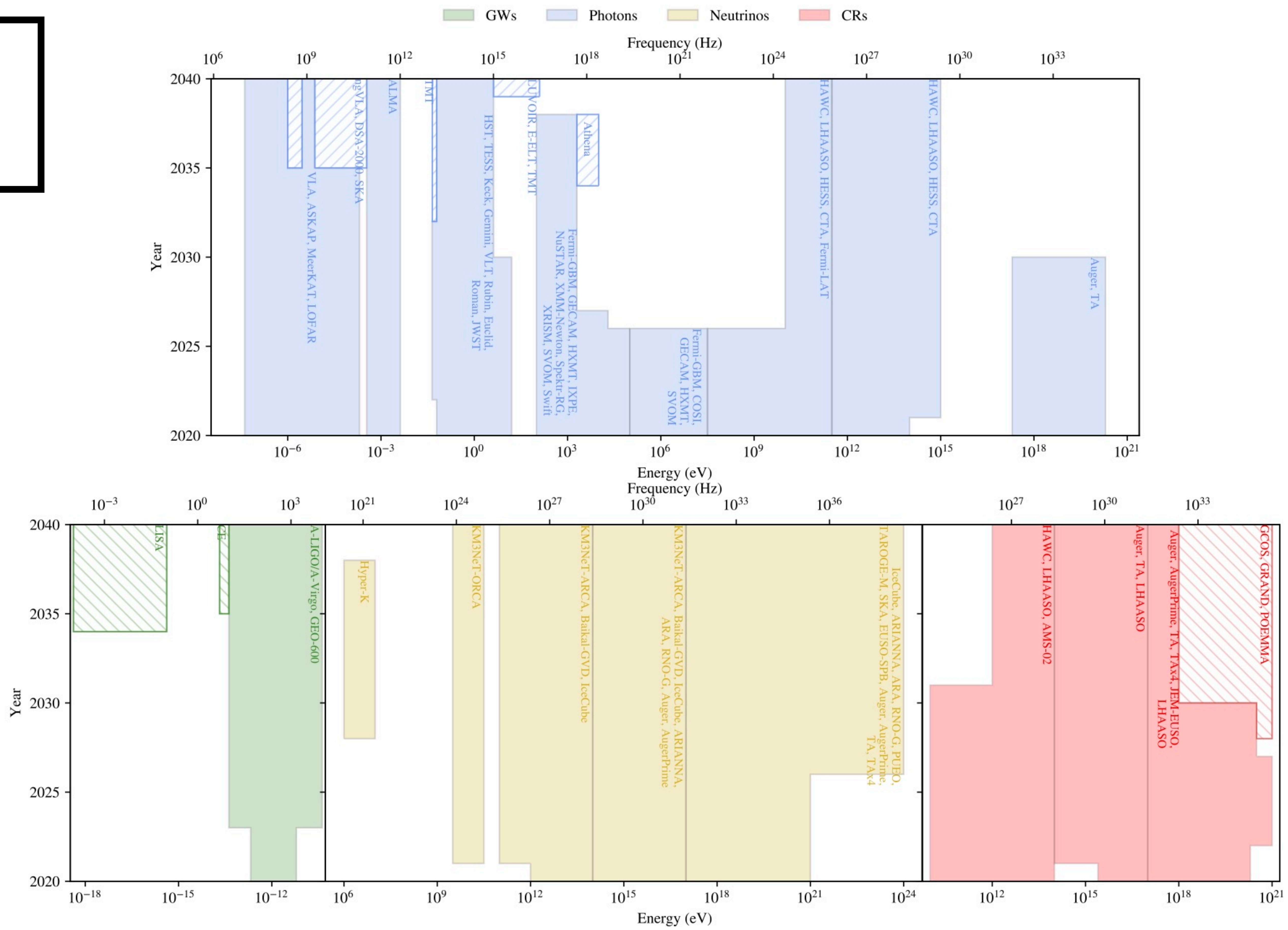
https://asd.gsfc.nasa.gov/mossaic/

Extra Slides

Mission Landscape for MMA of Massive Binary Black Holes

Aging missions and short-term bandaids leading to a early onset MeV-GeV blindness. How do we fix this?



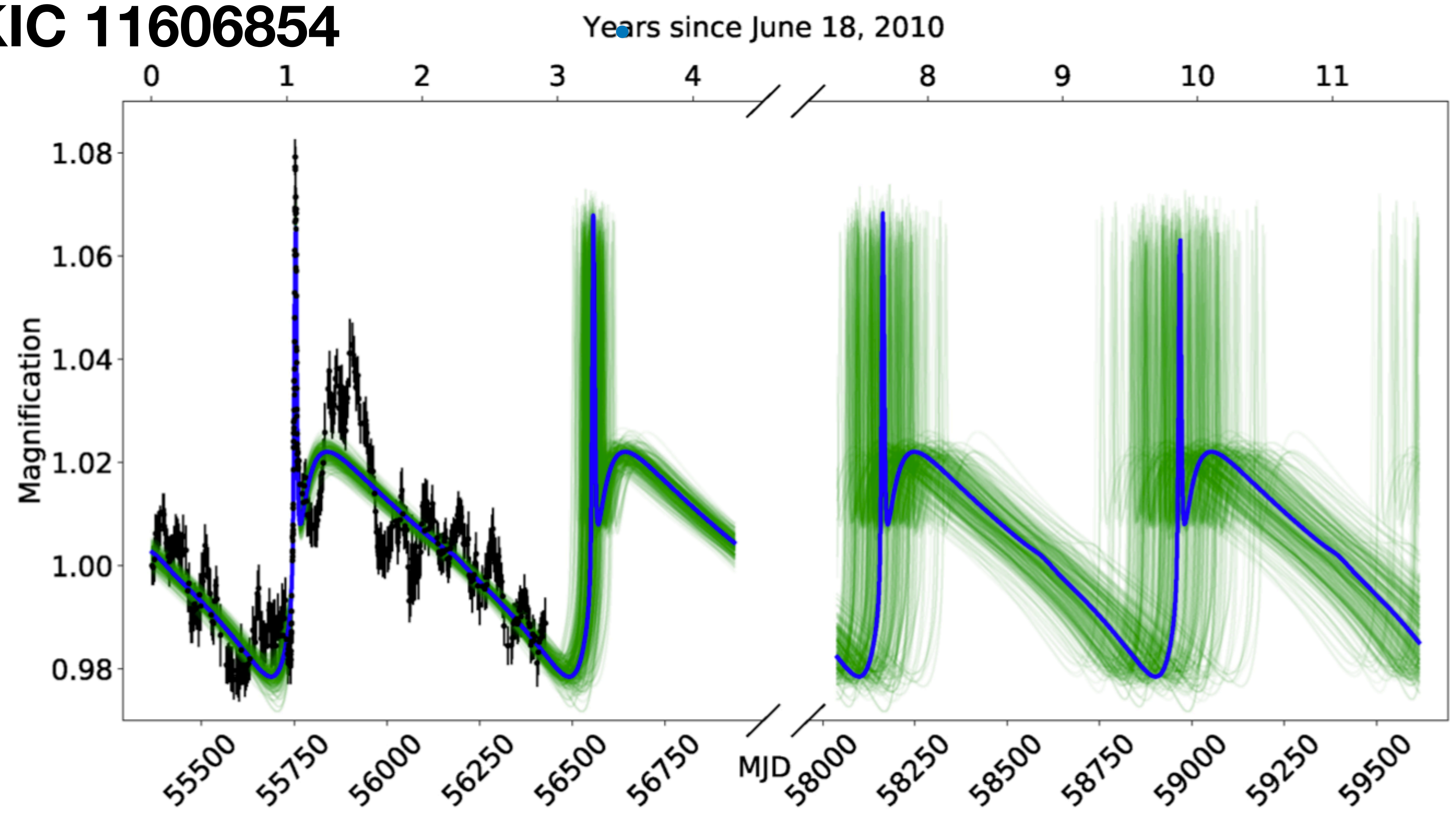


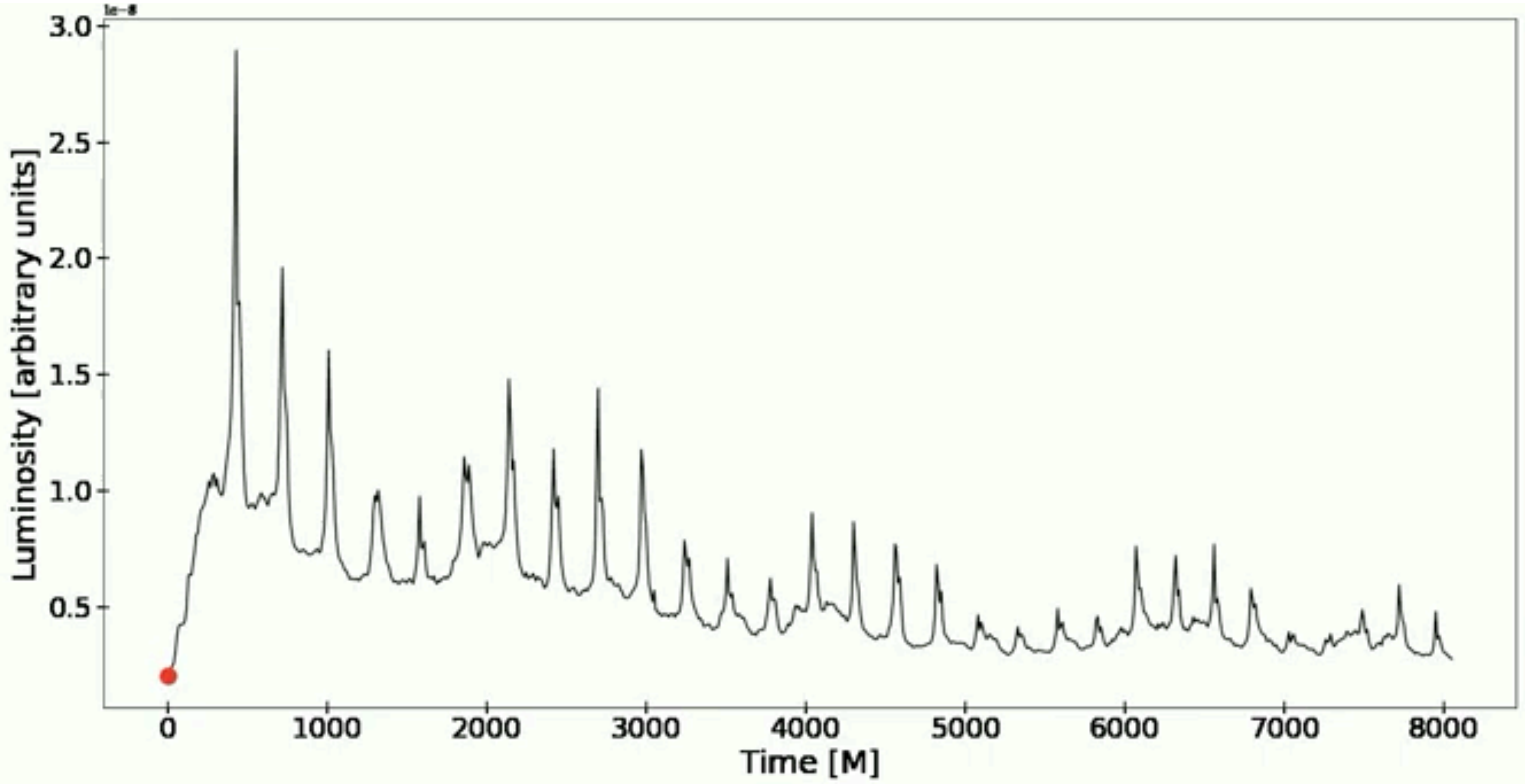
- MMA SNOWMASS Report: "Advancing the Landscape of Multimessenger Science in the Next Decade", Engel, Lewis, Stein Muzio, Venters, et al., arXiv, arXiv:2203.10074, (2022).

- Astrophysics LISA Working Group WP: Amaro-Seoane, Andrews, et al., LISA Consortium Astro Working Group, arXiv, arXiv:2203.06016, (2022).

• “Spikey” • Hu, D'Orazio, Haiman, Smith, Snios, Charisi, and Di Stefano, MNRAS, 495, 4061, (2020).

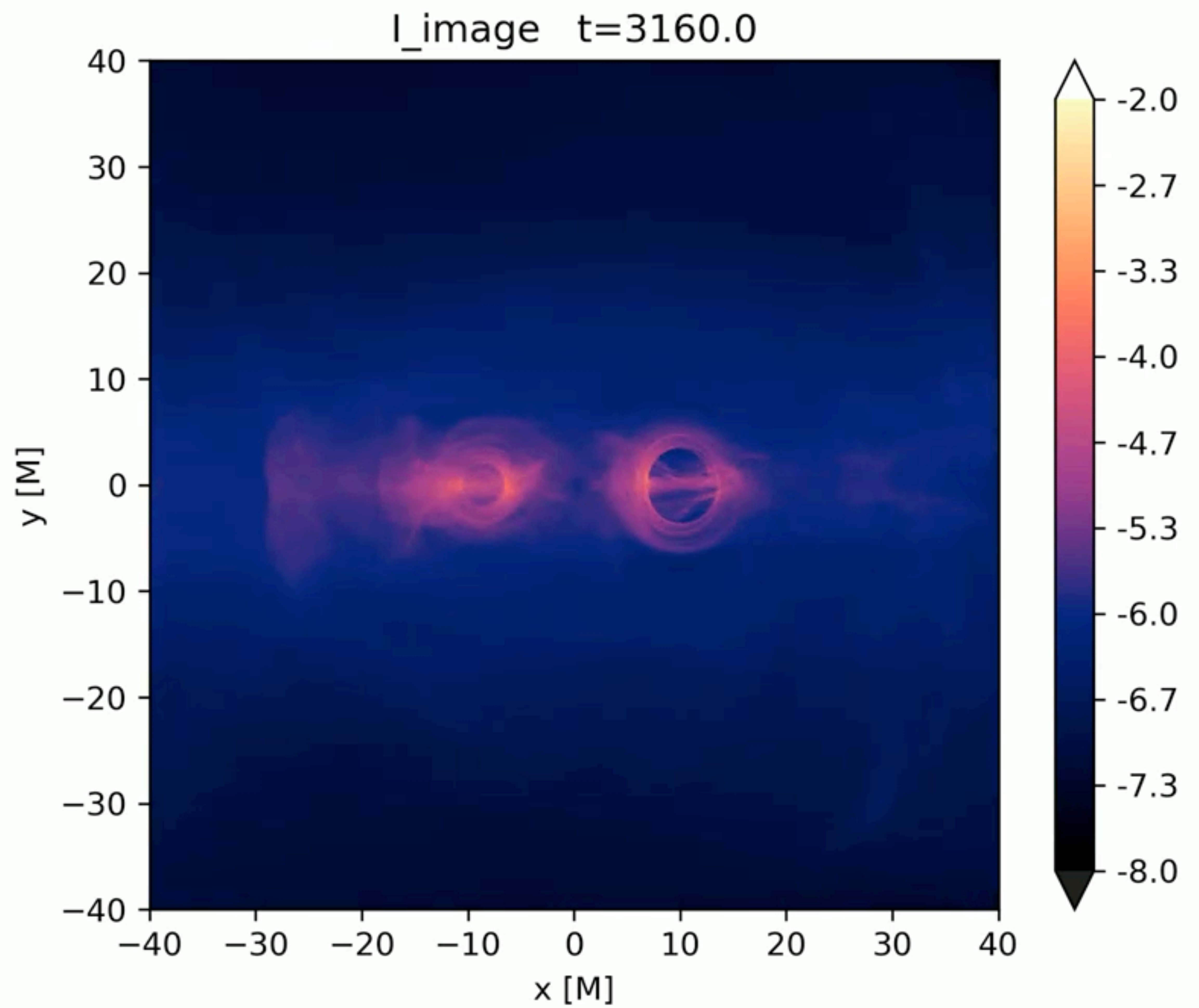
• KIC 11606854





Light Curves from Accretion onto Spinning BBHs

• Gutierrez, Combi, Lopez Armengol++(in prep)

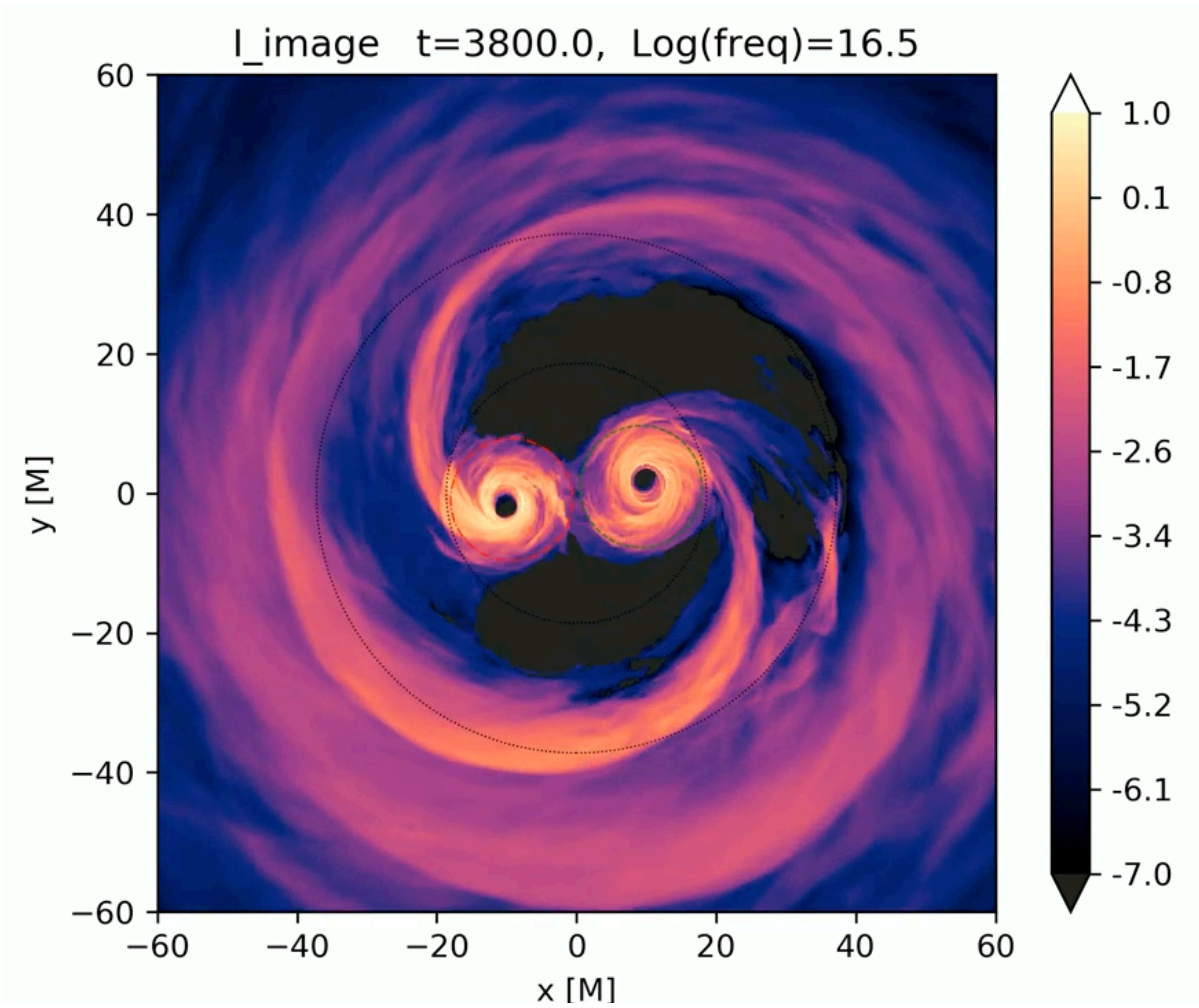


Spectra from Accretion onto Spinning BBHs

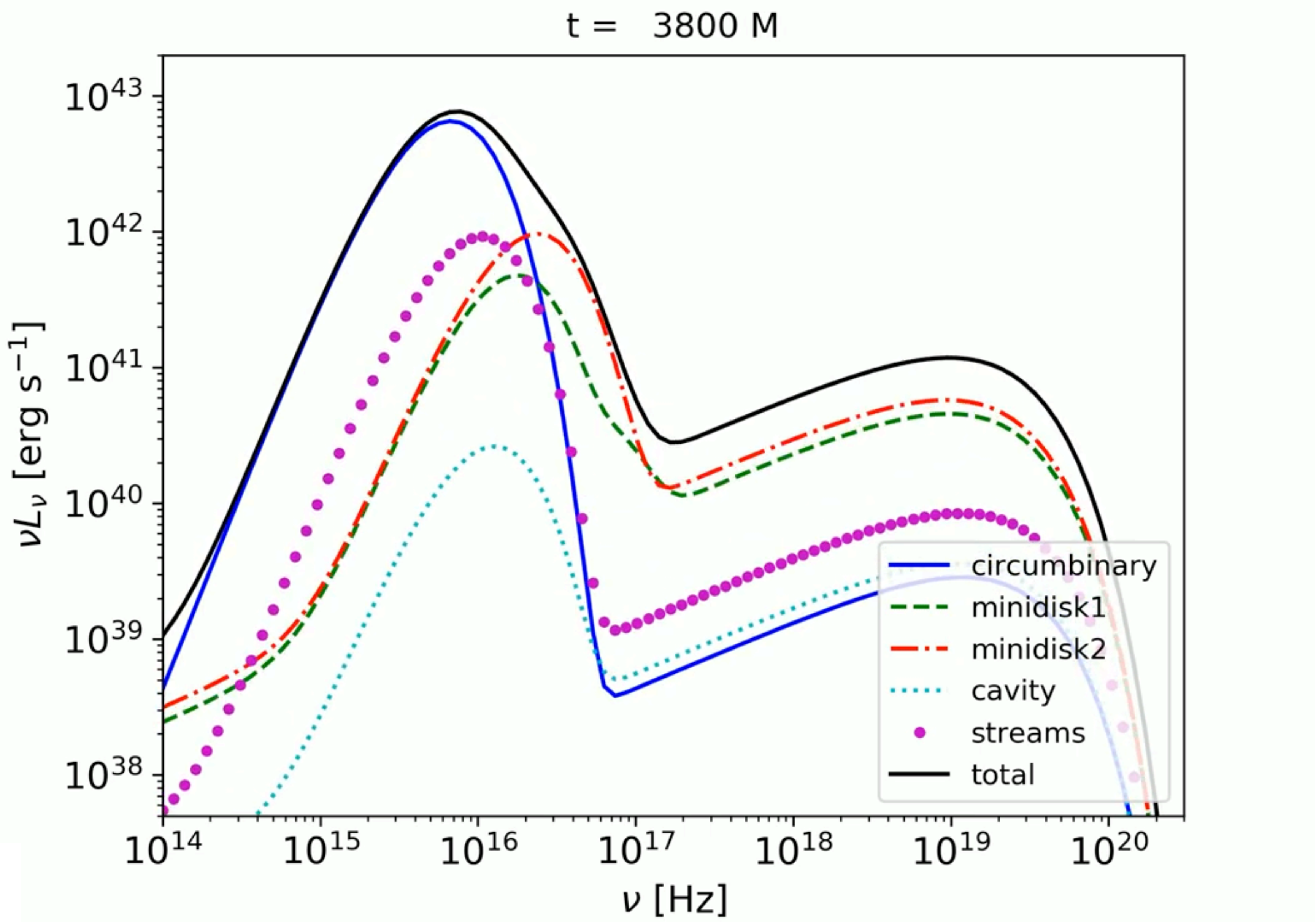
Gutiérrez, Combi, Noble, Campanelli, Krolik, López Armengol, and García, ApJ, 928, 137, (2022).

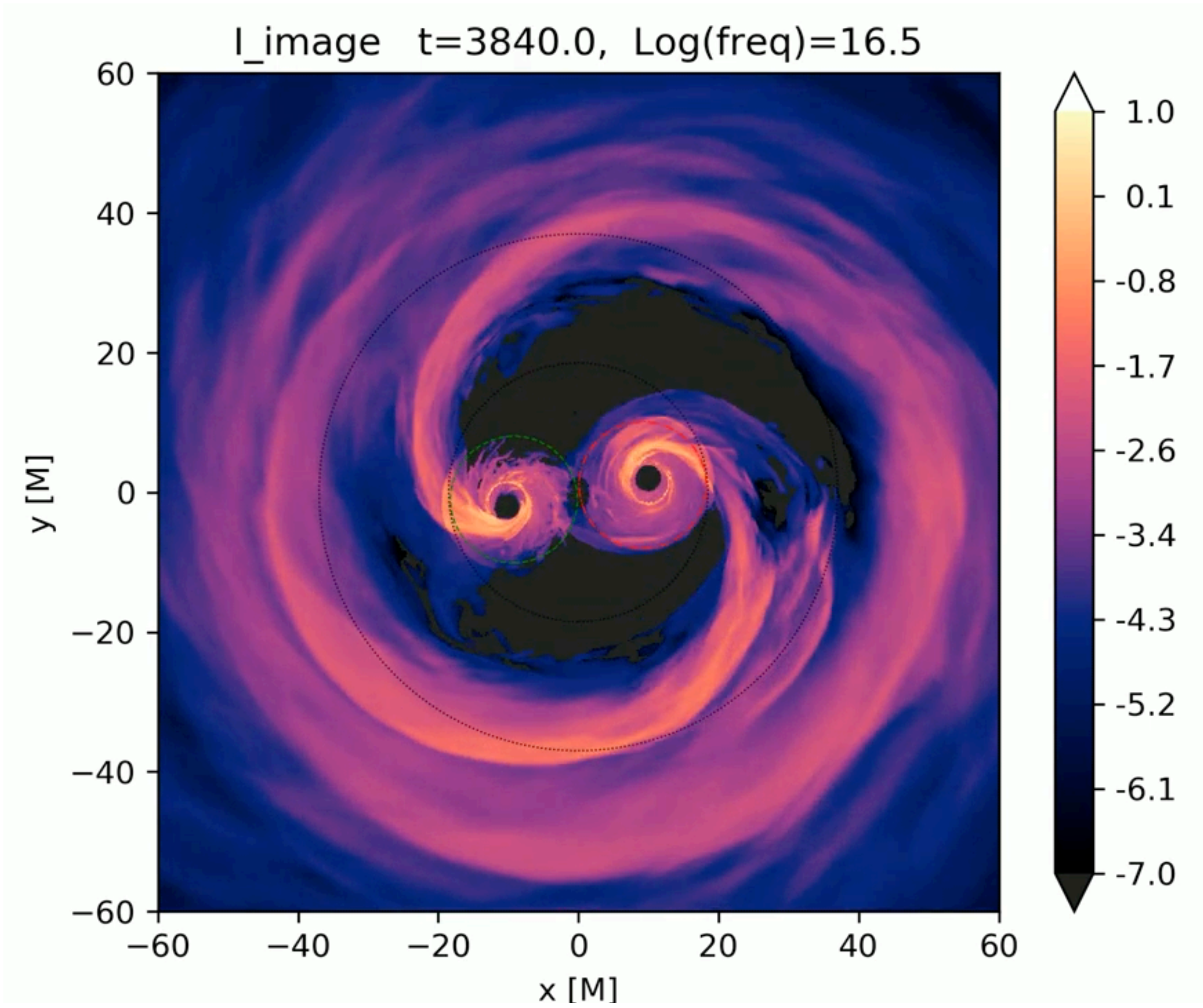
- **Following** d'Ascoli++2018
- **Using sim data from:**
- **BH spins (even at these modest values):**
  - **Brighter mini-disks;**
  - **More variable mini-disks;**
  - **More substantial mini-disks broaden the circumbinary disk's thermal peak;**

- **The spinning case provides new signatures to search for:**
  - **Broader thermal peak in optical-UV;**
  - **Variability in the UV on the binary's orbital timescale;**
  - **Stronger variability in X-rays;**



Spinning BBHs: a=0.6M, up-up





Non-Spinning BBHs